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THROUGH THE WEATHER HOUSE

THROUGH THE WEATHER HOUSE

or

The Wind, the Rain, and six hundred miles above

by

R. A. WATSON WATT

Illustrated

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PREFACE

"Through the Weather House" is an expanded revision of seven talks which the British Broadcasting Corporation invited me to give in the National Programme early in 1934. I would record my gratitude to the members of the Talks Department whose vigorous criticism helped in the formidable task of surveying the atmosphere in an hour and a half of talk, without benefit of picture. The expansion permitted in this small volume has not altered the main scheme of treatment adopted in the talks.

The intention is very far from that implied in the phrase "every man his own weather prophet"; it is no higher than an attempt to describe the rather intractable raw material with which the weather prophet has to work, and to exhibit it in relation to the atmosphere as a whole. In this attempt I have not avoided that extreme over-simplification of the processes at work which is the price of brevity. I have tried to tell nothing but the truth; I have not even tried to tell the whole truth.

It would be tedious, were it possible, to enumerate the debts which I owe to individual works on meteorology. Those skilled in the art—for whom this book is not designed—will recognize how much I owe to the writings of Sir Napier Shaw, to the official publications of the Meteorological Office, and to the Quarterly Journal of the Royal Meteorological Society. To the material taken from these sources I cannot claim to have added anything—save, I hope, a certain picturesqueness and, I fear, an uncertain inaccuracy.

If I have, in the end, conveyed the impression that, although the meteorologist's lot is not an entirely happy one, he is a misunderstood man mainly because we who listen to the broadcast weather reports have not learned to translate into longhand the meteorological shorthand in which these reports must be written, I may have, after all, added something more.

The reader who gets tired of counting floors in the Weather House and prefers to think of full scale heights will remember that each "floor" is ten kilometres high, so that the ground-floor extends to ten kilometres from the surface, the first floor occupies the interval between ten and twenty kilometres up, the second twenty to thirty, the *n*th extends from

$10n$ to $10(n + 1)$ kilometres. An occasional confusion between the nth floor and its equivalent the $(n+1)$th storey is unlikely to be important, and the frontispiece provides an elevation of the house which will, it is hoped, remove any ambiguity.

My friend and father-in-meteorology, Mr. C. J. P. Cave, M.A., J.P., Member of the International Commission for the Study of Clouds, has increased my indebtedness to him—already great—by providing from his very beautiful collection of cloud photographs the examples which illustrate the chapters on the Stair Carpets and the Lifts.

R.A.W.W.

These, sketchily, are reasons for talking about ourselves as living in the Weather House, for looking at the happenings in the air about us, for taking stock of the disappointingly little we know about it, for discarding some of the " weather wisdom " of the more assured morning papers, for thinking about the vast tracts of real weather wisdom that are still to be opened up. If we look up the address of this Weather House in the *Directory to the Universe* which the astronomers have been compiling for us, we shall find it tucked away, somewhat insignificantly, at No. 3 Sun Street in Galaxy No. X. In Sun Street Mercury lives at No. 1, Venus at No. 2, Mars at No. 4. No. 5 is a tenement with a vast population of minor planets ; Pluto, rather a newcomer and a bit of a dark horse, lives at the cold end of the street, at No. 10. Without any voyaging through time and space, to inspect the other thirty thousand million—or three hundred thousand million—stars of our galaxy, and the five million or so other galaxies, we shall find enough grandeur in the Weather House itself to keep us properly humble. Especially when we find time to talk about the price of the weather we shall feel economically very small.

This book is not to explain why the weather

happens, hardly even how it happens. It will get little further than describing where it happens. This atmosphere, this ocean of air on whose bed we live and move, this insubstantial peel of the terrestrial orange, which we are calling the Weather House, is a many-storeyed house. The lowest storey of all, the Ground Floor, is the one in which our familiar everyday weather of wind and cloud, rain and snow, fine and fair, warm and cold, unrolls itself. The ceiling of this ground floor, as we shall soon discover, is about six miles above our heads, and this figure lets us build up a working picture of the proportion which the ground floor, the true weather layer, the Troposphere as the learned call it, bears to the whole structure. How big is the house? We know that its floor—the ground we walk on, the oceans we sail on—covers two hundred million square miles, rather awkwardly wrapped on a ball which is spinning like a top. How high is the house? That, unfortunately, is one of the perfectly reasonable looking questions which do not have a perfectly reasonable answer. It either does not mean anything or it means too many things, because this house has no roof, it just fades out, very gradually and unobtrusively, as we go upstairs.

There is much that we can infer about the upper storeys, but we look now at just one thing we can see and measure, with fair certainty, from down below. I shall have to speak fairly often about the Aurora Polaris, the Northern Lights or Merry Dancers, which are rarely seen from Southern England, seen a few times a year from Northern Scotland, seen almost every cloudless evening from Northern Norway. We can measure the actual heights in the Weather House at which these exceptionally beautiful displays of decorative lighting take place. It turns out that the lower fringe of the curtain of auroral light comes down, usually, to about sixty miles above the floor, the topmost hem has sometimes been measured at six hundred miles up. Let us take the ground floor as our unit of planning, let us defy the architects by making every storey of the Weather House the same height. Then we can say that the House is more than a hundred storeys high, and that we can see some, at least, of the singularly beautiful decoration of the tenth to the hundredth storeys. Above the hundredth we shall not look ; but we shall not go to the other extreme and keep our eyes fixed on the ground floor, however important it is in our everyday lives. A hundred storeys may suggest a sky-

craper, but that would be quite a misleading picture, however attractive. For we must remember the ground plan of two million square miles—forgetting for the moment that it is wrapped on a ball—and compare it with the mere six hundred miles of height above which we have agreed not to look. The Weather House is more bungalow than skyscraper. We may get a clearer picture if we make the Weather House into a kind of Queen's Dolls' House, by bringing the earth down to the scale of the dome of St. Paul's. The hundredth storey will then be only nine feet out from the solid dome, the ceiling of the ground floor will be only a single inch out. Yet all we shall have to say of the weather itself has to do with the happenings in this one-inch shell. Some day we may understand the relationships between the upstairs tenants and the ground-floor people; though meanwhile they are very obscure indeed, the key of the ground floor may well be found in the hands of an upstairs tenant.

How far upstairs can we ourselves climb? What kind of messengers can we use to bring us information from the storeys to which we cannot yet climb? We know a great deal about the ground floor, knew it by looking up from

below, and had it confirmed and extended when balloons and aeroplanes began to get up to or near to its ceiling. Sometimes, indeed, they go plumb through the ceiling into the first floor, which is called the Stratosphere. The highest level to which man has yet climbed in the Weather House is just short of the ceiling of the first floor. This stratospheric first floor has been news of late, because the first stratospheric tourists have been making their way to these hitherto unvisited regions—first the Belgians, then the Soviet explorers, then the Americans. Meanwhile the official honours are with the American party, who, in the sealed gondola of their balloon, reached eleven and a half miles above ground.

All above this first floor must be explored by non-human and indeed by inanimate messengers ; a vast deal of human ingenuity has to be applied to devising them and to deciphering the messages they bring. The simplest messages which we get by what I may call artificial means are brought back by recording instruments attached to free unmanned balloons, usually called *ballons-sondes*. The instruments are very light, and when the balloons burst they parachute back to earth, to be posted to the Observatory by the finder, who finds his

thanks partly in the satisfaction of aiding science, partly in the very small pecuniary reward offered on the label of the instrument. Such devices have brought us messages from halfway up the third storey; beyond that height again we must use still less gross messengers. We shall find that sound-waves bring us back a message—in a code which is not entirely easy to read—from the fourth storey. And the fullest and clearest messages about the ninth to the thirtieth storey or thereabouts are brought by wireless waves which we send up and catch after they have been up and down again. Some of the messages about intermediate floors, and the little we know about the topmost storeys of all, come to us "by courtesy of" certain visitors from abroad whom we shall meet in later chapters. Meanwhile we note that the higher we want to push our exploration of the House, the finer and more tenuous must our messengers be; first the heavy aeroplane, then the floating manned balloon, then the *ballon-sonde* with its spidery aluminium instruments, then the sound wave in air, finally the tiny waves of light which alone add a few fragmentary messages about the topmost storeys of all to the reports which they themselves, and our other messengers, bring us from the inter-

mediate and lower storeys. But in the next chapter or two we shall talk mainly about the Ground Floor and its furnishings.

II

AN ALL-ELECTRIC HOUSE AND ITS WIRELESS

We shall not look for the front door of the Weather House: we are inside now, we have been crawling about on the floor all our lives. This floor, the surface of the earth, has features which are of very great importance in weather making. The fact that the Weather House is spinning like a top is itself important. The floor is partly land and partly—indeed mainly—water; the Weather House is one of these ultra-modern places where the swimming pools are excessively large and important. The land parts are very far from smooth—the unsmoothness of the ocean parts is a sometimes painful but not very important aspect of the Weather House. In our dolls'-house model, Mount Everest projects an inch from the model earth, Mont Blanc half an inch, Ben Nevis a mere sixth of an inch. But much smaller projections than these apparently minor roughnesses make vast differences to the run of the weather, especially to rain-making.

Lastly the floor of the Weather House, like

the floor of a Roman villa, is the heating surface for the whole ground floor. That may sound dreadfully old-fashioned, but the whole truth about the heating process sounds, on the other hand, very up-to-date. For the Weather House is, in fact, an all-electric house, taking its supply from the great power house of the Sun. And the supply is taken " by wireless ".

The sun's rays are wireless waves, very short-wave wireless indeed, but identical in nature with the waves used in broadcasting. It is a curious fact that the ideas of the newer wireless communication are nowadays familiar to everyone, while those of the age-old process of taking heat by wireless remain rather unfamiliar. And so it will be convenient to talk about the old by comparing it with the new.

In broadcasting, then, we know that the sounds made in the studio do not travel to our ears as sound, they must be converted into variations in electric waves, which are sent out from the broadcasting aerial. We can only get back to sound by letting those electric waves fall on a wireless receiver which is attuned to the particular wavelength which carries the programme we want. The receiver has two purposes. In the first place it is there to respond to waves of the particular wavelength desired

at the moment, to the exclusion of others, and in the second place it is there for the express purpose of turning their inaudible burden into audible sound. Now every warm material is a wireless transmitter, in the sense that it sends out electric waves which are like those used in broadcasting, except that they are very much shorter—say a hundred-millionth of the broadcasting wavelengths ; the hotter the material the shorter are the wavelengths which carry its main " programme ".

This wireless radiation from warm substances will, when it falls on other substances, tend to make them warm if they are tuned to the appropriate wavelength. And as they warm up they too act as wireless transmitters, sending out wavelengths depending on their temperatures, wavelengths which are therefore likely to be different from those falling on the substance and producing the warming. It is, then, true to say that we are all wireless transmitters and that we are all wireless receivers.

We turn to apply these generalities to the Weather House and how it makes use of the Solar Regional Programme. The sun is our particular local station in the celestial broadcasting network. The sun is very hot, and so the greater part of the energy which it radiates

is broadcast on very short wavelengths. Some of these wireless waves are the right wavelength to stimulate the wireless receivers in our eyes, and we see the sun, as we see everything we do see, by wireless. Some of the still shorter wavelengths do not find the eye-receivers tuned to them, but they find wireless receivers in our skins ready to respond to them by way of sunburn. Some of the longer waves also find appropriately tuned receivers in our skins, and they are converted into warmth. Just as we ourselves are wireless receivers, so is the floor of the Weather House, the surface of the earth, a wireless receiver, ready tuned to turn the wireless waves of sun-rays into warmth. Dry air, on the other hand, is not tuned to respond to solar wireless, and so it does not get itself warmed by the Solar Regional Programme. Water-vapour in the air is a good wireless receiver, but its main tuning range is to longer waves than those of Solar Regional.

It is very important to remember these different responses. We may perhaps fix them by concentrating on the apparently paradoxical but perfectly true statement that " the sun's rays are not hot ". They are only capable of heating substances which are appropriately tuned to their particular wavelengths. They

come from a hot body, but they make us warm only because we, and things around us, are tuned to them. They do not produce appreciable warming of the air around us because it is not tuned to them. But there is another very important process following from the warming of the earth. We have seen that every warm substance is a wireless transmitter, sending out waves which are shorter in wavelength as the substance is hotter. So the short waves of the sun warm up the earth's surface, and that surface in turn sends out wireless waves, but of longer wavelength, because it is much cooler than the sun. Terrestrial Regional, then, is at once a long-wave station and a relay station, sending out on its longer wavelengths the heat programme which it picked up from Solar Regional. Now this longer wavelength programme is in the tuning range of water-vapour, and so, though the water-vapour in the atmosphere is warmed hardly at all by Solar Regional direct, it is warmed very effectively by Terrestrial Regional relaying Solar. The water-vapour in turn shares its warmth with the air which contains it. Clouds, as we shall see, are made up, not of water-vapour, but of actual liquid droplets (or solid crystals) produced by the condensation of water-vapour in circum-

stances which we shall soon discuss. Both solar and terrestrial radiation can produce warming of these droplets, but the longer wavelengths of terrestrial radiation are much more effective in this case also.

We turn now to the differences in the behaviour of land and water surfaces in response to solar heating. The land is very much more easily heated up than the water ; for equal supplies from the sun it gets hotter, and gets hot more quickly, than the water. Moreover, the heating is applied to a comparatively small amount of material, which therefore heats up quickly. This is because the solid land presents always the same surface to the incoming radiation, so this thin surface layer alone is heated by direct pick-up, the underlying strata are heated only by a comparatively slow and ineffective diffusion of heat into them. The sea, on the other hand, because of its fluidity, presents an ever-changing surface, and the water which has been heated by direct pick-up is carried down by turbulent mixing processes to share its heat with water at considerable depths, while water from such depths is, in similar ways, brought up to the surface, there to play its part in the direct reception of the heat programme of Solar Regional.

"Lightly come, lightly go" is good physics as well as good psychology. The land surface, which so readily reached a comparatively high temperature in a comparatively short time, gives up its heat by long-wave radiation, by the non-wireless process of direct heat-conduction, and by the loss of water-vapour (carrying its heat with it) by evaporation to the air above it, and it cools down very quickly after the solar radiation ceases to fall upon it. The water surface gives up its heat by the same processes—with evaporation taking a much more prominent place—but it gives up its great store of heat quite slowly. Thus the sea (with which, for short, we include the freshwater lakes and rivers) is the great stabilizer, the heat-storage tank in the central heating system of the Weather House.

But of course the sea is a great storage tank of another and more obvious kind. We have taken somewhat summarily for granted the existence of water-vapour in the air. The sea is the main reservoir for the renewal of this water-vapour supply in the never-ending cycle of changes which we call weather; evaporation from water surfaces, and from moist land surfaces, when they are warmed; diffusion of water-vapour into the air; its transport by the winds;

condensation into cloud or fog, into rain, snow, sleet or hail ; and flow back of streamlet and river into the great reservoir.

The land heats up quickly when the sun shines upon it ; it gives much heat and some moisture to the air above it. The sea heats up slowly, it gets less hot, it distributes its store of heat to greater depths, but it gives some heat and much moisture to the air above it. And by these processes we have got the raw material of weather making, warm moist air, more or less warm, more or less moist. Our next discussion must deal with the weaving from this raw material of the cloud fabrics which carpet the great staircase that leads to the ground floor ceiling, but, singularly enough, not through it to the first floor.

III

HOUSEHOLD BALANCE AND REFRIGERATOR

"HEAT expands, cold contracts"—a pound weight of air takes up more space when it is warmed than when it is cold, a cubic foot of cold air is heavier than a cubic foot of warm air, if the pressure is kept constant. Having reached chapter three of a weather book without mentioning the word pressure, we find ourselves unable any longer to forget the barometer, the "wedge of high pressure over the British Isles", the "area of relatively low pressure over Iceland". We have to choose among several ways of looking at the barometer and its story, and there is good reason for looking at it in a way distinctly different from that in which the science of weather grew up. The barometer is, in fact, the household balance of the Weather House, it is essentially a weighing machine, and a tendency to forget that it is a weighing machine has slowed down the progress of weather science. What this weighing machine tells us is the weight of air which is sitting on top of the barometer; it weighs the

whole rod of air, from the base of the barometer to the very top of the Weather House, that would be contained in the barometer tube if it reached right up to the top of the house. The likeness to a household balance is pretty close ; you remember that the old-fashioned barometer was a J-shaped tube, a long leg on one side closed at the top, a short leg on the other open at the top. The air had been taken out of the closed tube, and the glass top carried the weight of air above it, so that it did not press on the mercury in the long leg. But on the open side the weight of the whole rod of air was sitting on the top of the short rod of mercury there. The very bottom of the J, then, was the fulcrum of a pair of scales in mercury, on one side the weight of a long rod of mercury, on the other that of a short rod of mercury and a very, very long rod of air. The balance was an automatic one ; if the long rod of mercury did not balance the load on the other side mercury flowed round the bend till balance was reached. And in that state the weight of the long rod of mercury, from its top down to the level of the top of the short rod, was the weight of air on the other side of the balance. The newer aneroid is the spring balance of the Weather House kitchen, in it the air is weighed by the amount

it compresses a spring, and like the domestic spring balance the aneroid is at once more convenient and less accurate than its older-fashioned relative.

The barometer, then, weighs the whole pillar of Weather House, from bottom to top, which is resting on it, and you will see that though we used to read it in " inches of mercury " that was rather a concealment of the weighing operation ; now we read it in millibars, which is a more convenient and honest way. The average barometer reading in the British Isles is not far from a thousand millibars, and a barometer reading of a thousand millibars tells us that the whole of that hundred-storey pillar of the Weather House which sits on a square foot of earth weighs just about one ton. It will now be clear that this is the same as saying that it would take a ton of mercury to fill a barometer tube which had a bore of one square foot. When the reading of the barometer goes up by ten millibars to " 1010 mb ", another twenty pounds weight of air has, somehow, been added to the pillar of one foot square cross section. When we know exactly how the extra twenty pounds has got there we shall know a very great deal about weather-making.

We shall look in a later chapter at the domes-

tic economy of the Weather House, but meanwhile we can get an indication of the scale on which it operates by realizing that the familiar enough process in which " an extensive low-pressure system is crossing these islands in an easterly direction " involves the lifting of some hundred thousand million tons of air out of that bit of the Weather House which has its foundation in the British Isles, and putting that quantity back again when the depression has passed over. How does the raw material of the weather, which we traced in our last chapter, take part in this housekeeping on the grand scale?

Warm air is lighter than cold air, and if we could tie a label to a particular pound packet we should see it float upwards, while the cooler air around it flows in underneath to replace it. We have to satisfy ourselves about the reasons for the warm packet stopping *en route,* we must discover why it does not float right up to the hundredth storey. There is a good deal to be explained, because, as it rises, the packet finds less weight of air sitting above it, and would therefore at first sight seem likely to go on expanding and rising. The main limit to this process is set by something called "dynamic cooling ", something whose results are more fami-

liar than its name, and whose opposite is perhaps more familiar than the direct process.

Anyone who has pumped up a bicycle tyre with a hand pump knows that the barrel of the pump gets hot. That is because of " dynamic heating ". When air is suddenly compressed as in this example it is compressed by the trapping of a barrelful and the pressing down of the pump piston on it, it becomes hot. " Suddenly " has a special meaning here : it means " so quickly that it has no time to share heat with its surroundings ". The opposite process, of " dynamic cooling ", is illustrated by the chilly feeling of the air which escapes from the bicycle tyre when the valve is just opened. Here, however, there is a complication to our simple experiment, due to the cooling effect of a stream of air playing on a moist hand, an effect which has its applications to weather problems, but which we need not discuss here.

The domestic refrigerator is another device which, in one of its forms, illustrates, and indeed depends on, dynamic cooling. The vapour of the working fluid is allowed to expand, it cools dynamically, steals heat from the contents of the refrigerator, and is then pumped round the cooling coils on top of the refrigerator there to give up its stolen heat to the air of the room.

Cooled thus to room temperature, the vapour is again subjected to dynamic cooling by expansion, and so the extraction of heat from the inside of the refrigerator, to be given to the air of the room, goes on.

Our selected packet of rising warm air, as it rises, expands, because there is a smaller weight of air above it as soon as it has floated up above its starting point, and as it expands it cools dynamically. Thus, although we started it on its course by making it warmer than its surroundings, this natural process intervenes to correct the excess, and it soon finds itself at a level where it is at the same temperature as the air about it. There is then no difference in pressure and no difference in temperature to distinguish it from its surroundings, and there it comes to rest. All the air in the ground floor of the Weather House has taken part in movements of this kind ; all the air above the surface layers has experienced dynamic cooling, and so it comes about that the air aloft is colder than that at the surface. Although this air above is—albeit only a very little—nearer the sun, the source of heat, we know that the source of heat is not effective in heating the air directly, that the heating effect must be relayed by the earth, and the dynamic cooling process ensures

a fall of temperature as we go upward from the earth. Hence the snow-capped peaks ; hence the electrically heated clothing of the modern Icarus. The original Icarus lost his wings not because he got nearer the sun, but because he was a good wireless receiver and was overheated by the Solar Regional programme.

There is a flaw in the argument as we have built it up. Going back on it we find that, since the air into which our sample packet is rising is itself colder and colder as we go up, the argument depends on the sample packet getting cold still faster, so to speak, as it goes, because it had an original excess of heat to lose before it could be brought to uniformity and thus to rest. We have not yet given any reason for the fall of temperature of the rising sample being greater than the fall of temperature with height of the successive layers of surrounding air through which it finds itself rising. We know that in actual fact actively rising dry air will lose 5½° F. in temperature for every thousand feet. And we know by measurement that on the average our thermometer will fall by only 3½° F. per thousand feet as we carry it upward to take the general average temperatures of the layers through which our packet is rising. If, then, our sample packet started with the very

considerable excess temperature of 10° F.—and it would be difficult to keep it from starting its climb before we could give it this excess—it would climb through about five thousand feet and then come to rest because it was now like its neighbours. But we have yet to consider why 3½° F. and not 5½° F. "All the air in the ground floor has . . . experienced dynamic cooling (and heating) and so it comes about that the air aloft is colder. . . ." Why then does it not wear the mark of 5½° F. per thousand feet which is the label of active mixing of this kind? The reason is that the mixing is not continuously active, and that there is a constant process of interchange of heat by wireless between the different packets of air, an interchange always trying to make the colder packets warmer, and the warmer packets colder, tending to uniformity of temperature throughout. It is the effect of this exchange of wireless programmes between different layers of air that reduces the rate of fall of temperature with height, one process tends to give 5½° F. change per thousand feet, the other 0° F. change per thousand feet, and on the average a compromise at 3½° F. change per thousand feet is reached.

The principal ingredient of weather making has got itself left out of this chapter ; without

STRATUS see p. 43

water there is no weather. The presence of water-vapour explains the exchange of programmes we have just mentioned ; we have already said in Chapter II that it is a good wireless receiver while dry air is a bad one and so water-vapour has much to do with the striking of the temperature compromise. But it has another extremely important part to play, in Chapter IV.

IV

DAMP IN THE WEATHER HOUSE

WITHOUT water there is no weather; there is no hope of weaving cloud fabrics out of dry air. In dry air the processes we discussed in the last chapter would have involved the sample packet of warm dry air in going much further before it cooled to similarity with its new neighbours; the presence of water-vapour in the *surrounding* air did much to shorten its voyage. It would however have had a dull and uninteresting voyage in any case; its total cargo of available energy would have been so limited that nothing very much of interest would have come of the voyage. Would things have been very different had it itself carried, as cargo, a load of water-vapour? Our sample packet of dry air is, in actual fact, able to carry with and in itself a load of the invisible water-vapour which is such an important ingredient in weather making. The proportion of this ingredient which it can carry depends on the temperature, the warmer the air the more water-vapour it can take up, and for every temperature there is a proportion of water-

vapour which cannot be exceeded—save in exceptional and temporary circumstances which we shall have a later occasion to consider. When this proportion is reached the air is "saturated", and the cooling of saturated air involves getting rid of some of its burden of water-vapour. The water-vapour in excess of that which corresponds to saturation at the new, and lower, temperature is released as liquid water drops, or as ice crystals, and becomes visible. The boiling kettle does not emit clouds of steam, for steam, as the engineer knows it, is invisible, is, in fact, the invisible water-vapour we have been talking about. The kettle sends out water-vapour which, mixing with the cooler air about it, saturates the air, and, having produced saturation, yet provides more water-vapour than can be carried by this cool air. The excess condenses out in tiny liquid droplets which, catching the light, give the familiar white woolliness of cloud.

The richest attainable mixture of air with water-vapour, saturated air as it is shortly and not quite accurately called, depends very greatly on the temperature, and not so greatly on the overall pressure. (That it depends at all on the pressure has nothing to do with the water ingredient; it is merely because a pound

of dry air takes up more room at lower pressure, and so there is, so to speak, more room also for the water-vapour that can go with it.) We shall think only of the usual 1000 mb. pressure. Then, for every pound of dry air we can take, at the freezing point of 32° F., a sixteenth of an ounce of water-vapour. At 50° F. we can double this amount, at 70° F. double it again, so taking a quarter of an ounce of water to a pound of dry air ; at 110° F. the proportions become an ounce to the pound. At the highest true air temperature recorded anywhere in the ground floor the mixture might have risen to such richness as to contain over two ounces of water to the pound of dry air. The weight of water carried may be less, it cannot normally be more, for the temperature stated. If now the process of heating, raising, expanding and dynamic cooling of the last chapter is applied to moist air, the cooling process may be carried to the point at which saturation is reached, and any further cooling will produce condensation of the excess water, droplets will be formed, and a visible cloudlet will result whenever the process is carried out on a sufficiently extensive scale in the open atmosphere. And with this condensation process comes in that other extremely important effect of water which we

have to discuss in this chapter. The invisible water-vapour, in its change to visible liquid drops or solid crystals, sets free its "latent heat", about which we must talk for a moment.

When we boil a kettle we give a supply of heat, from the chemical changes of burning coal or gas, or from the curious release of heat which occurs when an electric current fights its way against the resistance of a not very well conducting material, to the water in the kettle. For a steady rate of heat supply we get a steady rate of rise of water temperature until a parricular temperature, the "boiling point", 212° F., is reached. And then the temperature fails to rise any further. Copious clouds of steam are given off, the water in the kettle diminishes in quantity, but the temperature obstinately refuses to rise above 212° F. What is happening to the heat supply we are still steadily pouring into the kettle? It is, in fact, being used up in tearing the molecules of the water away from one another, it is doing the work necessary to turn the closely coherent visible liquid water at 212° F. into the free invisible vaporous water at 212° F. But it is not wholly lost, it is merely "latent heat"; when the vapour condenses again to a liquid it is released once more as heat, and the condensa-

tion process will only go on if provision has been made for carrying off the " latent heat " thus released, now no longer latent but active ; active as a brake on the cooling process which is producing the condensation, but active also as opposing that same cooling process which was bringing our sample packet to a condition of similarity to its neighbours. The store of " latent " heat is so great that the fraction of the total store which is made active by the condensation of a small excess of water at any moment quite offsets the effect of dynamic cooling. The sample packet of moist warm air is thus encouraged to seek still higher levels ; the water vapour contained in the packet is a powerful driver towards further ascent as soon as it begins to condense out as liquid water or as ice. Indeed it gives up a still further secret hoard of " latent " heat in going to ice, but that is also so small compared with the heat released in going from vapour to liquid that we need not consider it. What we must remember throughout our discussions is that the intervention of water-vapour, with its gift of hoarding latent heat, in this weather-making process, is the essential agency by which thousands of millions of tons of air may be enabled to climb from floor to ceiling of the ground floor. The motor

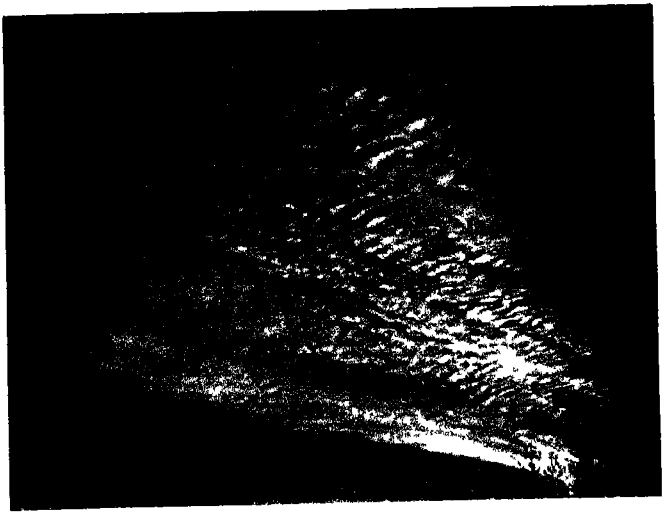
car carries its fuel as a liquid which it turns to vapour as required ; the rising air current carries its " fuel " as water-vapour which it turns to liquid as required ; the heat thus released reduces by more than half the rate of cooling with ascent.

It would lead us away from our main theme to say more here about latent heat, but it should be added that the refrigerator of Chapter III is an old-fashioned one, and that most modern domestic refrigerators carry heat away, from the chamber to be cooled, as latent heat.

Now we have before us, in these four short chapters, the whole machinery of the weather house, the power-house of the sun, the wireless transport of heat energy to the earth, the differing absorption of the energy by land and sea surfaces, the negligible absorption by dry air, the somewhat more effective absorption by moist air, the warming of the air by contact with land and sea surfaces, the taking up of water-vapour by the air in contact with moist surfaces, the expansion, rising and dynamic cooling of the resulting warm moist air, the resulting fall of temperature with increasing height, the modification of that fall by wireless exchanges, the arrest of the ascent of air when the rising current finds itself like its new neigh-

bours, the condensation of its burden of water-vapour into liquid drops if the cooling processes—whether those of dynamic cooling or of mere mechanical mixture with cooler air, as in the steaming kettle—are carried far enough, the release of the latent heat of vaporization when condensation takes place, the need for redistributing this released heat if the condensation is to continue, the encouragement of continued ascent as a means to this redistribution. These are the processes by which the ground floor of the Weather House is continually being refurnished and redecorated, and their application and results we must think of in the next chapter or two.

Meanwhile, so long as the recipe for saturated air is fresh in our minds, it is well to remember that the comfort of the ground-floor inhabitants depends very much on the failure of the air around them to maintain saturation. Saturated air, especially at high temperatures, is very uncomfortable stuff to live amongst ; the comfort of the aerial furnishings of the ground floor depends very much on their cooling power, and that cooling power is very dependent on their ability to carry off water vapour, with its store of latent heat, from our bodies. Thus it is that a hot day can be delightful if the air is far from



ALTO-CUMULUS. See *p.* 14

carrying its greatest permissible load of water-vapour, intolerably uncomfortable if that saturation burden is approached.

V

THE SPENDTHRIFT TENANT

ALL day the sun has been shining, the earth has been receiving steadily the Solar Regional programme, it has been converting much of this incoming wireless programme into warmth, and it has, in turn, been relaying the programme on its own longer wavelengths of Terrestrial Regional. All through the day the book-keeping has been on sound business lines, a handsome income from the sun, a modest expenditure from the earth, a comfortable net balance of warmth. But now the sun has set in the cloudless sky of a calm evening, and the book-keeping takes a new turn. The income page is blank, the expenditure side still shows outpourings from Terrestrial Regional, there is a growing debt of stored heat energy given up to the continued manufacture of long-wave outgoing radiation, and the ground chills rapidly. Water, the great stabilizer, intervenes ; moist air, lying stagnant on the earth, gives back to the now chilling earth some of the heat which it had taken up from the warm earth of afternoon. But this restoration cools the moist

air, and the chilled air can no longer carry its full burden of water-vapour. The " dew point ", the temperature of saturation, is reached, the proportion of water that can no longer be carried is deposited as dew on chilled solid surfaces, especially on those, such as metal roofs and railings, which can carry quickly away the heat released by condensation. And so, first on metal work, then on stones and plants and soil, a coating of dew is laid down. If the chilling has gone so far that the surfaces are below freezing point, then solid hoar frost or rime appears instead of the liquid drops of dew.

But that is not the only, not the most serious, result of spendthrift radiation. The air near the ground is not merely moist, it is dirty. Especially in and about big towns, where the antiquated folly of burning soft coal in open domestic grates persists into an otherwise moderately civilized age, the air is loaded with soot, sulphuric acid and assorted salts. As the cooling process sets in, the excess of water in the chilling air will condense on the tiny particles of more or less dirty dirt, each of which is itself overspending by turning its own tiny store of heat into long-wave radiation, and so getting cold, chilling the damp air in contact with it. The resulting droplets go on cooling by over-

spending, more water accumulates on them, they grow bigger, the result is fog. "All along o' dirtiness, all along o' mess." If we heat our houses, raise our steam, the right way, we shall banish bad fogs; the householder, nowadays, is a worse culprit than the modern factory, just because the factory is modern, and the householder is not. We shall banish *bad* fogs, we shall not banish fogs. There will still be coast and country fogs, because even clean dirt, salt from the sea, dust from the soil, will be there as nuclei of condensation. But these fogs—even the sea fogs—are not the sources of universal trouble and loss, of danger and death, that the sooty town fogs are. Banish soot and its chemical cousins and you banish town fog, because town air is warmer than country air, and so must do more overspending before it could produce fog at all, if only it were equally clean.

The fog, once produced by spendthrift radiation, is not readily dispelled by the next day's programme from Solar Regional. For fog is a poor wireless receiver, it does not convert the incoming radiation from the sun at all effectively into warmth, it reflects most of the radiation back towards outer space again without utilizing it, and so, too, without letting it reach the earth's surface, where it could be utilized

for heating. A good breeze is the great dispeller of fog. It brings up its own supply of warmer drier air, mixes it with the cold sodden foggy air, the new air swallows up the surplus water as invisible vapour, and we can see our way about again.

In a valley the cold, too-moist air of the calm misty night—mist is incipient fog, fog not yet so dense as to become an acute nuisance—lies stagnant in the hollow ; air chilled by contact with the rapidly cooling upper slopes drains down into the valley. The upper slopes are unhindered in their spendthrift radiation because the air, heavy on account of its coldness, flows downhill as would water, flows steadily away from them as it cools, instead of remaining to cover them with a mist blanket which would check their loss of heat, and so the whole valley below fills with a stagnant puddle of foggy air. Here, then, we have the particular fabric that clothes the bottom tread of the cloud staircase, the valley fog. In this process of fog formation spendthrift radiation is the principal and immediate cause of the condensation to a visible collection of water drops. On the higher steps of the grand staircase of the clouds, to be looked at in the next chapter, the immediate cause is dynamic cooling.

VI

CLOUD WEAVING

WE have said little or nothing as yet about winds, nor shall we have much to say about them till a later chapter. But this much we must say, in a single sentence, before we can climb the cloud staircase to its untimely end below the ground floor ceiling. The air currents which we call winds are produced by the unequal heating of different parts of the earth's surface, on a large or on a small scale. Their flow is modified—modified is indeed too mild a term for such a drastic transformation—by the spinning of the earth, but, no matter how they are produced, we have here to think what happens when they meet. Wherever we have converging winds blowing in towards any particular place, wherever, that is, we find that two windvanes more or less close together are not pointing in exactly the same direction but have the tails of the vanes closer together than their tips, then more air seems to be carried towards the point where the lines of the two vanes would meet than is leaving that point. There cannot be a steady piling up of air at the " bottleneck ".

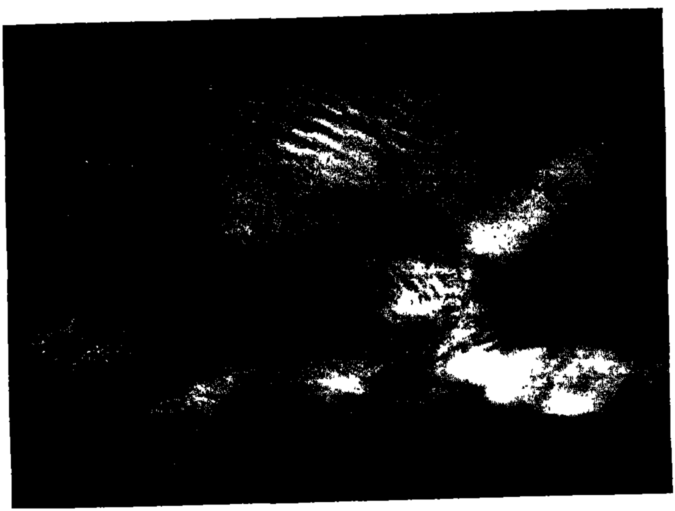
There is only one way in which this apparent piling up of air in one place can be avoided. The apparent excess supply that is going in horizontally must be got rid of vertically, the excess air converging towards one part of the floor must be rising towards the ceiling. This forced ascent resulting from convergence must, in turn, result in dynamic cooling, and if the conditions are such that the air reaches its "dew point" the excess water-vapour will condense, as visible droplets, on the dust particles which are to be found at all levels in the ground floor of the Weather House, and a cloud is formed.

We have twice, in the last few pages, found ourselves compelled to mention dust particles as nuclei of condensation in the formation of mist, fog or cloud. This suggests that, however briefly, we should explain why dust is so important in the formation of water drops. It is one of the most important of all the experimentally ascertained facts of science that water-vapour will not form drops at all readily—if at all—without some "nucleus" on which to condense. The absence of nuclei gives rise to the exception, mentioned earlier, to the limiting load of water-vapour in air of a given temperature. If there are not available nuclei the excess

water does not condense out, and the air mixture is not merely "saturated", but "supersaturated", it contains a greater proportion of invisible water-vapour than that corresponding to saturation at its particular temperature. Ordinary air contains an ample supply of dust particles on which condensation can take place, and indeed the counting of the microscopically small particles of dust in a sample of air is done by "growing" water drops on them. The air is made moist, suddenly expanded, and the dynamic cooling produces condensation on each dust particle, so that each is now represented no longer by an invisible small bit of solid, but by a quite large drop of liquid which can be seen and included in a count.

If the air is carefully cleaned of dust—and the best cleaning is done not by dry-cleaning but by this very process of loading up each particle with a water drop—then condensation takes place on any electrically charged particles that may be released in the air, on large "ions" (molecules with an unbalanced charge of electricity) or minute electrons, the ultimate particles of electricity. Much of our knowledge of radioactivity, of the structure of matter, and of cosmic rays, depends on the superlatively beautiful method by which Professor C. T. R.

CIRRUS (see p. 45)



To face p. 56]

Wilson first showed the path of an electron by the wisp of cloud which formed along that path in dust-free moist air. This paragraph is, however, an aside, our main concern is to note that cloud-formation requires, not merely air and water-vapour, but dust, even though the dust may be, at times, the dust of broken atoms.

We have found the stuff that clouds are made of, but how is it woven into the infinitely varied fabrics that are characteristic of the different steps of the grand staircase? The intimate details of the weaving process are still very obscure, no one has yet produced in the laboratory a real reproduction of our everyday clouds. But within the last year or two Sir Gilbert Walker has made imitation clouds which show very clearly and convincingly how the characteristic markings of cloud sheets depend on the fact that the air does not rise or fall in a uniform " lump ", but breaks up into cells whose edges are moving more rapidly up or down than their centres. He has shown, too, how much the shape of the cells depends on whether the overcooled and therefore too heavy air on the top of the cloud-forming layer is moving fast or slowly relatively to the warmer lighter air on the underside of the layer. We are beginning

then to understand the elements of cloud language, the pattern of the cloud tapestry tells us a story of the state of things governing its weaving.

VII

THE STAIR CARPETS

WE saw, in Chapter V, how spendthrift radiation wove the unpatterned fabric on the bottom step of the cloud staircase, the featureless mass of valley fog. Closely related to this fog mass is the fabric of the next higher step of the staircase, Stratus cloud, anywhere from ground to about 1000 feet up, an almost formless featureless sheet, which disperses by breaking up into large shapeless, fluffy tufts of fracto-stratus.

The next higher step has a fabric which anyone writing in years other than the drought years of 1933-4 might have called a too-familiar fabric. If the conditions in the lower layers of the ground floor are such that condensation takes place gently from a comparatively slow sustained uprise of moist air, an uprise which though slow is persistent and might almost be called " relentless ", then there is formed, oftenest at levels between 1500 and 3000 feet, in the lowest tenth, that is, of the ground floor, the sombre grey sheet of nimbo-stratus, from which falls, by the continued release of water drops

by dynamic cooling, our main supply of rain, the gentle rain whose beneficence was a little forgotten till the wells ran dry.

The fourth step of the staircase is the Strato-cumulus step, at some 2000 to 7000 feet above the ground, not yet so much as a quarter way to the ground floor ceiling. Now the cloud fabric is developing a much more definitely marked structure, the stair carpet here is indeed still in rolls and bales, though they display a somewhat brighter surface than the nimbo-stratus of the step below. And strato-cumulus may be taken as marking, not merely a step but a landing on the staircase, for it is the topmost of the group of low clouds, Stratus, Nimbo-stratus and Cumulo-stratus. Above them come two steps of "middle" cloud, somewhere about 10,000 to 20,000 feet up, and called Alto-stratus and Alto-cumulus. Alto-stratus is an almost featureless grey sheet—stratus in a cloud name always suggests a relative lack of pattern. It is grey because it is thick enough to weaken the sunlight which gets through it, although the sun may be seen dimly gleaming through it; the watery sun of alto-stratus is an important weather sign. Indeed, the development of alto-stratus is a very characteristic stage in the particular display of cloud fabrics

which unfolds step by step, from above, with the approach of a depression.

Alto-cumulus, as opposed to alto-stratus in its watery sourness, is rather a jolly-looking cloud. We have talked of clouds in general, and valley fog in particular, as cloud-blankets, but alto-cumulus is more like a cloud quilt, for it has biggish rounded masses or discs, arranged in lines and rows, which give it a quilted appearance ; the French call it the " big sheep " cloud, which is very graphic, and distinguishes it from the " little sheep " pattern of the next higher step.

This higher step, the lowest of the " high cloud " group, is the Cirro-cumulus layer, the mackerel sky, which has much finer quilting. Sometimes it is rippled like the sand on the seashore ; it is white with very little shadow, and usually forms above 20,000 feet. It is a cloud sheet that suggests, perhaps a little deceptively, fine weather, summer evenings, holidays, little flashes of sunlight from dancing wavelets. It is the most lovable of clouds, but in actual fact it often means changeable weather.

Climbing still, we come to the topmost steps of all, Cirro-stratus and Cirrus. Cirro-stratus is like a refined edition of alto-stratus, making a thin veil of whitish cloud, sometimes just giving

a milky appearance to the sky, sometimes having a fibrous structure like a tangle of silvery spiders' webs. This veil often produces halos around the sun or moon. Cirrus itself is the magnificently varied group of delicate thread-like clouds up between 25,000 and 35,000 feet, which appear, often in an otherwise blue sky, as wisps and streaks and long bands of feathery cloud, tufted filaments, ostrich feather plumes, and mares' tails, these latter not to be confused with mares' nests, of which meteorology has its share.

Here, on the topmost steps of the cloud staircase, we are among the ice-clouds. The cirrus group is made of ice crystals, not of water drops. It is probably safe to say that whenever an upper cloud fabric has a fibrous structure it is an ice fabric and not a water fabric ; this rule applies to the fibrous brands of alto-stratus as well as to the cirrus clouds. And here, among the ice-clouds, we reach the ground floor ceiling. It is no decorated ceiling, it is graced by no cloud fabric. Yet, invisible as it is, it is a very real ceiling indeed. How do we recognize it ? We have climbed the cloud staircase to six miles up, and it has become steadily colder and colder. We left the floor heated to some 40° F. or 50° F., we lost about a degree Fahrenheit for

every three hundred feet we climbed, now we are far down among the minus readings of our thermometer—not indeed a mercury thermometer, for the mercury froze at about five miles up, and we have climbed another mile since then. What shall we find if we climb a few miles further? First we shall find no cloud staircase to guide us, but what more? We shall look upward in a later chapter, but for the moment we take one backward glance down the staircase with its three roughly equal flights between landings, the high clouds, cirrus, cirro-stratus, cirro-cumulus in the topmost flight; an imaginary landing four miles up—two-thirds of the way from floor to ceiling—marks the change to the middle-cloud flight, alto-stratus and alto-cumulus; another imaginary landing two miles up and we are down among the low clouds, strato-cumulus, nimbus, stratus, and the valley fog. And, looking down from the cirrus level, we remember that there is an express cloud-lift, the cumulo-nimbus, which also serves the cirrus level, and a quieter lift, the cumulus, which seldom passes the four-mile landing.

VIII

THE LIFT SHAFTS

We have seen that the grand staircase which leads to the ground floor ceiling is carpeted with cloud fabrics of very different texture, from the cotton-wool of the fracto-stratus through the serviceable stuff of the strato-cumulus, to the organdies, chiffons and tulles of the cirrus. But the Weather House staircase is supplemented by two lifts, a comparatively quiet lift of ordinary speed, which is called the Cumulus lift, and a turbulent express lift called Cumulo-Nimbus. We shall get unnecessarily tangled if we try to show here that both are hydraulic lifts, that the one grows out of the other, and that the express lift has a great deal to do with the electricity supply of the Weather House, though all these things will show themselves true as we go along.

In discussing the general process by which cloud fabrics are woven we thought, for the sake of clarity, of a single neatly labelled packet floating up through a uniform sea of surrounding air whose state was in marked contrast to that of the packet. That picture, like all pic-

tures used to illustrate meteorological processes, is too simple, too sharp in outline, to be a safe guide to the truth. But it is much more nearly safe in illustration of how the lift clouds, cumulus and cumulo-nimbus, are formed than in the case of the stair-carpet clouds which we have already discussed.

The cumulus cloud, which builds up in a towering mass from a moderately sharply defined flat base, to a very sharply domed top, breaking out into a riot of rounded protuberances, amazingly hard and " solid " looking, of a dazzling white when the sun is behind the observer as he faces the cloud, is a typical summer-day cloud. It marks the summit of a well-defined vertical air current, heavily loaded with moisture. This current reaches, at the flat base-surface, the level at which condensation takes place, and continues, partly because of the momentum acquired in its upward rush, mainly because of the release of " latent " heat in the condensation, to pile up above that surface. It is very characteristic of cumulus formation that in a sky with many cumulus heads the bases are all very closely at the same level, they define a widespread, nearly horizontal surface at which the conditions necessary for condensation of water-drops from the uprising

air are, for the first time in the ascent, satisfied.

The starting of a cumulus lift is one of the few meteorological processes which we can see being effected by human agency, though not under human control. On a hot summer afternoon, heavy and oppressive with moist air, breathless under a yet unclouded sky, a smoker forgets for a moment the admonitions of the B.B.C. Thoughtlessly he drops a lighted match in a thicket of gorse, and in dropping it he touches the press-button of a cumulus lift. As the column of hot air and smoke from the resulting heath fire rises it will be seen to reach a level at which the dark smoke is no longer the most prominent label of the ascending column, a sharp line of copper-tinted cloud appears, and above it builds up the familiar cauliflower head of a genuine small cumulus cloud. This is the clearest example possible of one of the paradoxes of dynamic cooling ; the violent heating of the air by the fire results in such cooling that its burden of water-vapour condenses out as cloud.

If, on the still grander scale on which Nature operates without the aid of man, the uprush forming the cumulus is still more vigorous than that leading only to the " cauliflower head " formation, the cloud head develops through

mountainous towers to the throwing out of fibrous streamers which often spread in the form of an anvil, and we have the typical thunder cloud, the cumulo-nimbus. In this express lift the condensation is so rapid and so vigorous that showers of rain or snow, of hail or "soft hail" fall from the cloud base. The violence and the local character of these thunder showers is an index of the violent uprush of the moist-air lift in its comparatively narrow lift-shaft, capped by the cloud itself. The streamers which float from the towers of the cloud head are often of a delicate cirrus structure which tells us unmistakably of an ice-crystal fabric.

The real state of things in this hydraulic lift-shaft is very clearly revealed by the hailstones which fall through it, but before we can read their story we must learn a little more about the water supply of the Weather House.

This is, however, an appropriate point at which to discuss the lifts as passenger lifts. It is fair to say that the aeroplane and airship pilot disliked these lifts not so much because of the electrical troubles which occur in them—see Chapter XII—but because of the way they buffet him mechanically. The newest race of pilots, however, the glider enthusiasts, seek them out and utilize them as genuine passenger

lifts, it is on uprising currents of air that they must depend for their carriage to higher levels, and the success of the glider pilot depends on a *flair* for finding a lift "going up" when he requires one. He may get a good start by being catapulted into the uprising air due to a wind blowing against a hillside, but once started he watches for the cloud-label at the top of the lift-shaft and boards the moving lift. Doubtless for everyday use he prefers the ordinary lift, but he is getting more and more daring, and in this summer of 1934 he has been making increasing use of the express lift, the violent uprush into the cumulo-nimbus thunder-cloud, as an aid to the steady destruction of the short-lived altitude and distance records for motorless flight. Both mechanically and electrically he is safer than the aeroplane pilot, much safer than the airship pilot, in the same environment, but he must occasionally have picturesque stories to bring back from these darkly disturbed districts high up in the lift-shaft.

IX

THE WATER SUPPLY

IT is not entirely illogical that rainfall has appeared in these pages only as a sort of by-product from the cloud-weaving looms. All-important though it be to the ground-floor inhabitants, it is merely the closing link in the chain of water-circulating processes which we have already traced. The processes began with the picking-up of a load of water-vapour, from sea, river and land surface, by relatively warm air which carried it aloft; this led to its condensation into the ice crystals and water drops of the cloud fabrics, whence it fell to earth again as rain, snow or hail. Clouds are always falling ; the crystals and drops of which they are made sink more or less steadily earthward by their own weight, against the friction of the air through which they must pass. The cloud may be constantly renewed by new condensation, the particles falling through its base may be evaporated by the effects of dynamic heating and by mixture with relatively dry air stirred into new proportions by turbulence, but if the condensation overcomes these moderating influences rain will fall.

There is a somewhat unexpected feature in the formation of water drops which might well have been mentioned in the discussion on cloud-making, but which is so important in rain-making that it cannot be left out of account in this chapter. Just how difficult it is to initiate the condensation process, to make the change from the state in which there is no water drop at all to that in which a very tiny drop exists, depends on the kind of nuclei available for condensation. There are some nuclei with such an affection for water that they withdraw it from unsaturated air, so that condensation may take place even before cooling has proceeded to the " dew-point " as ordinarily understood. Generally, however, the cooling has to be carried beyond dew-point, super-saturation has to be reached, before droplets are formed in appreciable numbers. But the moment the critical achievement, the formation of a minute droplet, has been effected, then the conditions are very drastically changed. For a minute drop itself helps further condensation upon itself, it tends to grow rapidly because condensation upon it is easier than upon smaller nuclei. And the larger the drop the more rapidly it will fall through the air in which it finds itself. That this must be so is seen by considering that

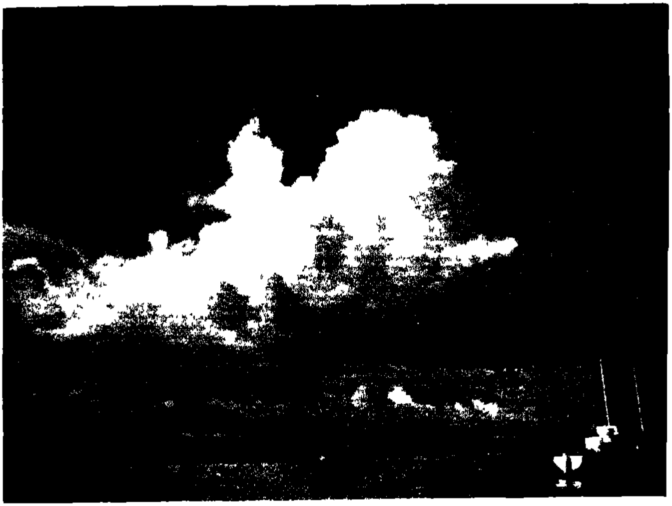
if we double the diameter of a drop we increase its weight eightfold, but its cross-section and its surface only fourfold. The downward urge depends on the one factor, the resistance on the other, and they will balance at a higher limiting speed than for the smaller drop. When the speed has risen to the value at which the hastening action of gravity is just balanced by the slowing action of resistance, this limiting speed of exact balance will be maintained. We must note that it is a speed relative to the air current through which the drop falls, not a speed at which it is approaching the ground. A sufficiently strong up draught will hold the drop suspended, a still stronger one will carry it upwards. The drops will then, if the conditions for condensation continue, grow rapidly until they do reach such a size that they can fall to earth through the up draught. The maintenance of a rainless cloud depends on a rather delicate balance of conditions, indeed one might almost say on a delicate departure from balance, for a mild degree of over-shooting the mark is probably an important factor in cloud-making.

The scale of rain-making operations may be visualized by remembering that a drop four-thousandths of an inch in diameter can fall to

earth through an upward current of about two miles an hour, and that the comparatively gentle currents of ordinary rain-making are not often stronger than this. There are, however, conditions of rain-making which are very different from this placidity. We have spoken of the hailstone as carrying a story of violent uprush in the lift-shaft of the cumulo-nimbus, and we are now ready to read the story.

A large hailstone, when cut in halves, will often be found to consist of a number of alternate shells, some hard clear ice, some comparatively soft and opaque like the core of the "stone", which resembles hard packed snow. How is this comparatively complicated projectile manufactured; how does the lift-shaft prove to be also a shot-tower, producing shot which even in Europe may reach the size of golf balls, which in sub-tropical lands may reach a weight of a couple of pounds or so?

The upward speed of the air in the lift-shaft may exceed eighteen miles an hour, and if it does exceed this value no water can fall to earth through it. For a drop big enough to fall against such an uprush would be too big to hold itself together, and it would break into smaller drops which would be carried aloft again. But solid hailstones can fall through this



CUMULUS "ORDINARY TYPE" *see p. 19*

updraught, and can reach the earth to tell us that such a fierce uprush exists. About two and a half miles from floor level, in temperate latitudes, the air temperature is already below freezing point. The top of the lift-shaft, however, is often about five miles up, so that the moist air which succeeds in getting into the upper part of it condenses out not into supercooled water drops (water drops remaining liquid despite freezing temperatures) but into ice-crystals, which grow into pellets of "soft hail" by the continuation of the direct ice-condensation process. This growth will bring the size and weight of the pellets to the point at which they can fall through the updraught. On the way down the pellet falls through a long stretch of saturated air, loaded with supercooled water drops formed at middle levels. As the updraught is constantly renewing these conditions, the length of this saturated column through which the pellets fall may be more like ten than five miles—the pellet, if we can mix our domestic engineering still more than we have done, can walk ten miles downwards on a vertical up-going escalator of moist air in getting halfway down from its five-mile top. The cold pellet, falling into warmer and warmer saturated air, collects on its surface a glassy

coat of smooth ice. It may, however, stagger sideways *en route*, or the up-rush may strengthen in its direct path, so that it is tossed up again, and a new soft coating is laid on it. A succession of such incidents makes the onion structure which was revealed in our inspection of the stone as it finally reached the ground.

Once in a while even the Weather House sees the label, "Lift out of Order". The violent uprush, which was carrying up with it all the water drops resulting from condensation, is suddenly arrested, the whole of the accumulated water is deprived of its support, and falls in a "cloud-burst". A cloud-burst is a lift out of order.

There are, as we have seen, two main kinds of rainfall. There is the widespread comparatively sustained and comparatively gentle fall from the slow and steady upward movement of air produced by converging winds. There is the comparatively heavy, brief and local shower, of which the thundershower is the best developed example. The latter, as we saw, is produced by the rapid ascent of a slender column of air, by a process which we described in dealing with the formation of clouds. It will be clear that anything which alters the rate of ascent of moist air will affect its efficiency as a

producer of rain. A wind blowing in from the sea against a mountain range near the coast, for example, will give specially heavy rain on the windward side of the range, because the air, heavily laden with moisture from the sea, is forced to climb the mountain side, and this forced ascent gives condensation and rainfall. The "wettest" rainfall recording station in England, Seathwaite in Cumberland, owes its distinction in this matter to such a reinforcement of the more general rain-making processes. It should however be said that Seathwaite is arid by comparison with the world record-holder, Cherrapunji in Assam. Seathwaite's hundred and thirty inches of rain per year, and the two hundred inches of some British mountain stations, are large compared with London's twenty-five inches, but not much when compared with the four hundred and thirty inches a year of Cherrapunji. Two hundred and seventy-five of these inches fall in one quarter of the year. This same process of forced ascent, not necessarily going as far as to give rain, explains the formation of such local cloud shapes as the helm cloud of the Peak District.

X

THE VENTILATING SYSTEM IN DETAIL

IT was fashionable in the earlier discussions of the architecture of the Weather House to treat the ventilating system as a comparatively simple general circulation, disturbed by the more or less accidental, though frequent, interventions of " local " processes. It is characteristic of the modern realism that this very broad treatment is no longer fashionable ; it is recognized that all the " local " influences add up not to disturb but to make the " world " picture. But the importance of the ventilating system makes it worth looking at the world picture as a whole, taking it mainly as a convenient summary of observed facts rather than as a statement of how the machinery works.

The general flow of the world's winds is the most important single element controlling the conditions of life and work in the very different rooms of the ground floor of the Weather House. Like all the processes of the house it is due, in the first instance, to the heating effects of radiation from the sun. These effects, as we

can infer from our previous discussions, depend very much on the relative positions of the great masses of land and water, and on the relation of these masses to the equatorial belt, where the radiation falls most intensely. The flow of the winds is modified, too, by the geographical and topographical features, by the heights of mountain ranges and by the nature of the country. The spinning of the earth on its polar axis has a dominating effect on air motion, and it was a convenient artifice to consider first how the ventilating system of the Weather House would work if the floor were all of one pattern, without contrasts of land versus sea, of high ground versus low, and then to consider how this " planetary circulation", as it is called, was changed by the realities of the floor. We should expect to find something like these simplified " planetary " winds over the great oceans, with greater and greater departures from planetary simplicity over continents and mountainous lands. Still more broadly we should expect the mainly oceanic southern hemisphere to be a region of mainly planetary circulation, as opposed to the much more mixed conditions of the north wing of the Weather House.

The general picture is more easily remembered in terms of pressure distribution than of

actual wind strengths and directions, but this further compression into a kind of architectural shorthand is of use to us only after we have learnt one or two rules about the relations of pressure distribution and air motion on a spinning globe. It is again characteristic of the newer outlook that, while the earlier treatment of these things would have been fairly definite in calling one " cause " and the other " effect ", the modern meteorologist is, for the present, content to deal with them as close relations, without giving one dictatorial powers over the other. They are, as it were, two languages in which the same story can be told: there is a steady state of mutual balance in which a given wind distribution means a given pressure distribution, in which, knowing only the pressure distribution, we can say very accurately what the run of the winds will be.

A packet of air " sitting still " on a hill top in Ecuador is, of course, rushing from west to east at a thousand miles an hour because of the spin of the earth on its axis, while a packet sitting still at the North Pole is sitting still also in the sense that it has none of that speed which is due to distance from the axle of the spinning globe. The packet sitting on the Tower of London has a west to east speed of 650 miles

an hour. If, now, we push the equatorial packet northward over the surface of the earth it will be too fast for its new neighbours, retaining the original west to east motion which kept it in step with its hilltop it will be running eastward relative to the slower ground of its new non-equatorial environment, a purely northward push will give not a south wind but a wind from west of south, a purely southward push will give a north-easterly wind. Anything which on a non-spinning earth would be moving in a certain direction will, because of the spin, turn to the right in the Northern hemisphere, to the left in the Southern hemisphere. We have shown the reason only for the simple case of a north and south push, for an east or west push the deflection can be seen to result from centrifugal force, the packet to which we give a westward push would be moving too slowly for its neighbourhood, and would slide towards the north, where the tempo is slower, a push towards the east makes the packet tend to outrun its neighbours, so it moves to a more southerly region where the environment suits its higher speed towards the east. Always, then, deflection towards the right in the Northern, towards the left in the Southern hemisphere, whatever the starting direction; a stronger turn-

ing tendency near the poles, where the change of surface speed with latitude is greatest, no turning tendency exactly at the equator, where, loosely speaking, we can see that the packet which is pushed too fast can find no faster environment, that which is slowed down can find equally slow neighbours either north or south.

This gyratory effect produces a flow of the wind which otherwise appears paradoxical. Suppose on an earth which is not, for the moment, spinning, we have a specially heavy column of air, a centre of high pressure. Then air will tend to flow out of the column until its weight, and thus its pressure, is reduced to equality with that of the surrounding air. This outflow will be directly, radially, outwards, and its speed will depend on the excess of pressure between centre and surroundings.

At this point, a little reluctantly, we must be introduced to the "isobar". We have seen that the barometer, the household balance of the Weather House, measures for us the weight of the column of air above it. We can, then, draw a map and write on it the weight of the column above each place, measured in this way. If, on this map, we draw a line through every place at which the weight is, for the moment, the same, every place at which, say, the barometer

reads 1000 millibars, that line is called the isobar (the line of equal pressure) of 1000 millibars. We can now draw another line through all the places of 1010 mb. readings, and this will be the isobar of 1010 millibars, and so on.

In the case which we were discussing before the isobars intruded we might picture a centre of highest pressure, with pressure falling gradually and uniformly as we went outward from the centre. The isobars in this case would be concentric circles at equal distances apart. The wind would flow along radii of these circles, and its strength, its rate of flow, would be greater the closer the isobars were together, that is, the greater the pressure gradient. This idea of isobars and pressure gradients will be easy to all who use contour maps to show them road gradients.

But the same causes on a spinning instead of a stationary earth will produce the additional deflection to the right which we worked out a little ago, and a steady state of balance can be reached in which the wind speed is indeed proportional to the pressure gradient, but its direction, instead of being exactly across the isobars, is exactly along them. Such a state could go on indefinitely but for new disturbing

influences. The simplest anticyclone, then, is represented by a high pressure area surrounded by closed circular isobars; along these isobars blow winds which, in the Northern hemisphere, circulate with the clock (for the outward flow is given a right hand, or clockwise spin by the gyratory effect) and which are stronger the nearer the isobars are together. The simplest depression, on the other hand, has a low pressure centre, and the winds blow against the clock round the isobars, for the inward flow which is tending to wipe out the low pressure is deflected to the right, giving a counter-clockwise rotation. That these states can persist is shown by imagining the air speeded up, slowed down, or deflected. Speeding up means greater tendency to turn right, which takes it towards the higher pressure, and the speeding up is thus opposed ; slowing down means turning relatively leftward, towards low pressure, and the motion is thereby hastened up to the state of balance ; the effects of deflection can be worked out in the same way.

This geostrophic (" earth-turning ") balance, as it is called, is a dominating influence in our latitudes, at the equator, as we have seen, it will be unimportant. In its place control is taken by the cyclostrophic balance, due to the centri-

fugal force of the air rotating about the centre of the isobaric system itself, the geostrophic and cyclostrophic controls are always present, the former predominates in high latitudes, the latter in low.

The disturbing forces which may destroy the persistence of the steady state which we have just built up are of two opposing kinds, and here again we have a balance, but a balance which is constantly being upset, now in one sense, now in the other. On the one hand are the heating effects which we have already discussed at such length, tending to set up new pressure differences, new motions of moist air, including the very important upward motions which we have left out of the present discussion. On the other hand we have the influences which interfere with air motion, the friction of air on earth, of air on air. The rubbing of the moving air on the rough floor of the Weather House will slow down the wind speed, and the wind will consequently turn inward toward the centre of a depression, or outward from the centre of an anticyclone. The rubbing of moving air on other air, involved in the mass of eddying whirls, big and small, which are covered by the general name of turbulence, has two effects, the first that it hands on some of

the energy of motion of one air packet to another, the second that it is steadily at work to diminish the energy of air motion as a whole, turning that energy into frictional heating of the air concerned. As a warming influence this conversion is not important, as a means of reducing wind speeds it is very important.

XI

THE VENTILATING SYSTEM IN GENERAL

Now that we have learned to translate from one language to another, now that we know an anticyclone to be at once a pressure system with high pressure at the centre and a wind system with winds blowing clockwise round it (if it is in the Northern hemisphere) and a depression to have anti-clockwise winds, with an inward tendency at the ground level, but parallel to the isobars when we have got up 1500 feet or so above the floor, we can establish our shorthand picture of the general circulation of air over the ground floor of the Weather House as a whole.

Starting with the equatorial belt itself we find a region of relatively low pressures, with a rather irregular run of the isobars, and light easterly breezes. Just off the equator this regime of irregularity gives us the doldrums with their light and variable breezes, and frequent calms, varied by heavy squalls, thunderstorms and rains.

Outside this belt we find a great anticyclonic girdle about 30° to 35° N. and S. latitude, with

five high pressure centres, one over each of the great oceans, north and south Atlantic, north and south Pacific, and south Indian Ocean. These great and practically permanent anticyclones give us the trade winds, which blow with nearly steady strength and direction all the year round. Day to day changes there are, but the seasonal change is mainly a slight movement of doldrums and trade winds to follow the sun, a movement northward and southward which is about six weeks late on the sun, and which is due, not to a movement of the centres of the great anticyclones, but to an intensification of these systems, each during its own summer.

Still further from the equator the difference between the wind systems of the northern and southern hemispheres, due to the land areas of the north, becomes marked. Throughout the year the southern ocean, about 40° S., has a low pressure area, while in the northern summer the northern continents are also the seat of low pressure areas. In northern winter, on the other hand, the northern continents are covered by anticyclones, while there are large low pressure areas, centred about 60° N. over the two great oceans, North Atlantic and North Pacific.

This arrangement of centres gives us, then, the easterly breezes of the equator, the rather unpleasant vagaries of the doldrums, the very dependable trade winds blowing at a steady ten or twelve miles per hour from north-east in the Northern, and from south-east in the Southern hemisphere. It gives, too, the greatest "cyclonic" circulation in the whole house, the Asiatic monsoon, which, although its main effect is found in the Indian Ocean, affects the winds of the eastern Mediterranean and of the China Sea.

So much for the lower ground floor; we can just make the beginnings of a similar picture for the region near the ground-floor ceiling. Observations on clouds and by sounding balloons are not yet sufficiently numerous to give us a detailed picture, but we know broadly that the circulation at some five miles up is, as we should expect, much simpler than at the floor level. There are large low pressure areas permanently centred over the poles, and these two depressions extend as far as 60° from their centres, to 30° N. and S., almost to the two boundaries of the tropical belt. In still lower latitudes there is an anticyclone over each continent, while the equatorial east wind is found all the way up from floor to ceiling.

That the easterly surface wind at the equator extended high in the ground floor was first revealed by still another of the less usual labels that we find attaching themselves to different items of the Weather House furniture, in a way which is very convenient for the surveyor. The catastrophic eruption in 1883 of the volcanic Krakatoa, a nearly equatorial island west of Java, left its mark on the skies for several years. The immense clouds of volcanic dust thrown up in the eruption spread, eventually, over the whole world, and produced, by processes of a kind which we shall discuss very summarily in Chapter XX, the most striking sunset colours ever recorded. The spread of the dust could be traced on its way over the ground floor, and it has left puzzles which still await solution. While the easterly direction of the air flow is not in itself surprising, its speed as shown by the dust cloud was surprisingly high, and there is no satisfactory explanation of how the air which carried the dust northward and southward over the whole earth acquired and retained these unexpected directions of flow.

XII

THE ELECTRICITY SUPPLY

When we speak of the electricity supply of the Weather House we must remember that we have already found that the house takes its light and heat by wireless from the sun, so that any local electricity supply is superfluous for these most ordinary applications. It must be confessed at once that we do not yet know what effect the local supply has on the everyday comfort of the house. It may be that the very obvious difference between the languor of the river valley and the exhilaration of the seacoast or the hilltop has a relation to the electric wiring of the Weather House. But, obvious as is the difference, its cause is as yet so obscure, so incapable of being caught by our measuring instruments, that we cannot discuss it here. And so we shall have much more to say about the things that happen when the electric system runs amok than about its everyday state.

Of the everyday state we can say this. There is somewhere a high-tension battery which keeps an average current of about a thousand amperes flowing into the floor continuously. A

thousand amperes is a moderately heavy current, but it is spread very thin in the Weather House, and it lends itself ill to utilization. If we wished to make it provide the five milliamperes or so that we want for a portable wireless set we should have to collect the current flowing into the floor of a Weather House room thirty miles square. Yet to drive these minute currents through the high electrical resistance of the atmosphere requires such high voltages that a suitable voltmeter—and it is by no means easy to provide a wholly "suitable" voltmeter—connected between the earth and an exploring probe a yard above ground would read a hundred volts or more. If we could put the probe at the ground-floor ceiling, without allowing any leakage at the intermediate levels, the voltmeter would read something over a million volts. It is one of the many unsolved riddles of the Weather House to explain how this million-volt battery is kept charged, or, to put the riddle another way round, how the floor of the Weather House can remain negatively charged in spite of the heavy average current flowing into it to neutralize its charge. An explanation may be found in a more refined kind of stone-throwing than that mentioned in Chapter XVII, or it may be found in the lift

shaft—with which we are concerned further in the present chapter—but for the present it remains in doubt.

The hundred volts per yard of height which was taken as a fair specimen of ordinary conditions in the electricity supply was a very rough average. There is, in fine weather in south-east England, a reasonably regular variation of this voltage with time of day ; it rises from 150, in the early hours of the morning, to a maximum of 270 about nine in the morning, then it falls to about 175 at two in the afternoon, rising again to 260 at nine in the evening. The current is carried by the motion of minute charged particles which rise or fall under the urge of the voltage gradient. These charged particles are, as we have already seen, important nuclei for condensation. When water drops form on the nuclei the whole particle becomes so massive that its mobility is much reduced, the speed at which the charges move is much reduced, that is to say the current is much reduced, and its effect in keeping the voltage from piling up is much reduced. In fog, for this reason, the voltage gradient may rise to ten or twenty times its normal value, to about 2000 volts per yard of height.

We return to the express lift, this time to

consider its singular doubling of that role with the role of a dynamo. Here again there is a considerable store of ignorance on which we must draw, but certain facts are firmly established, although the machinery behind them is still incompletely understood. The viscissitudes of water drops in the lift-shaft have, as a somewhat surprising consequence, the building up of very large charges of electricity at different points in the lift-shaft, and this building up, sustained as it is by the continued production, transport and breaking up of fresh supplies of water drops, may go on until very great voltages, ten million volts or more, exist between different parts of the cumulo-nimbus cloud, or between the cloud and the earth. When this building up has gone far enough to break down the insulating properties of the air a lightning flash takes place, and the voltage difference is temporarily destroyed. It may be built up again by the continued working of the lift, and so a thunderstorm is maintained by the hydraulic express lift acting as a dynamo. It is a generally reliable rule that a " lift " cloud is not ready to produce a thunderstorm until the characteristic brushing out of its cirrus streamers into the anvil shape has shown itself.

The lightning flash is such an impressive and

such a destructive member of the Weather House family that it has been closely studied in recent years. It is possible now to draw a much more accurate portrait of the flash than of its ancestry. First, perhaps, we should enquire why it is a flash, why it gives out light. We have already said so much about the radiation problem in wireless terms that it is merely a subsidiary stage of tidying up to add that the only way to send out wireless signals is to produce violent agitation of electrons. The London broadcasting station sends out its wireless signals by making electrons surge up and down its aerial wires a million times a second, the sun sends out its very large range of wireless wavelengths by oscillating the electrons in its constituent atoms and molecules in a very complicated fashion at a mixture of rates very much higher than this million a second. Rates of oscillation of about 400 billion a second give the particular wireless waves that we call red light, something just under twice that rate gives violet light. Roughly speaking we may say that when the electrons in an atom or molecule are violently disturbed light is given out, and a common way to produce the violent disturbance is to shoot at the atom or molecule with the debris of another atom, for example with a

fast-moving electron. A lightning flash, then, is the result of a dart of electrons which is shot from cloud to cloud, or from cloud to earth. The dart shakes up the air molecules, and light is given out, but this is only the beginning of a catastrophic breakdown. Many molecules are shattered, electrons are torn off them, and these new free electrons shatter other molecules, and so on, until we have a ribbon of molecular debris, full of free electrons capable of running freely up or down, and thus forming a path of low resistance carrying a heavy current, while the whole ribbon is aflame with the light given out by those electrons which have not been torn completely away from their molecules, but have yet been shaken violently from their normal orbits. The whole catastrophe is an avalanche of collisions between electrons and molecules, the collisions also produce sudden heating of the ribbon of air, this expands violently, and sound waves are sent out by the expansion, to reach our ears as thunder. The flash as seen is generally brief and decisive, because the difference in time of arrival between light waves from one end of the flash and the other is absolutely negligible, and because light from the flash reaches us almost exclusively by the shortest path. The thunder peal, on the other

hand, is long and blurred, because the sound from the distant end of the ribbon reaches us appreciably late, and because there is much twisting of the sound waves towards us by indirect paths. It must not, however, be taken for granted that all lightning flashes are over "like a flash of lightning", for one sometimes seems to be continuously visible, without any break at all, for a period of five seconds or so, as opposed to the customary very small fraction of a second. The writer of this book has seen many such flashes of long duration in a thunderstorm in the Ægean.

The average lightning flash is probably about half a mile long, and it consists of a succession of these electron avalanches, each lasting about a five-hundredth of a second, with quiet intervals of perhaps a hundredth of a second between. The rate of electron flow may become so great, under the urge of the thousand million volt pressure between cloud and earth, that currents of a quarter or half a million amperes flow at the climax of the avalanche.

To sum up briefly the life history of a lightning flash we may say that the mechanical processes in the express lift cloud cause a piling up of negative electric charges in one part of a cloud, or on the earth, and of positive charges

on the earth or in another part of the cloud. This piling up is continued by the mechanical forces working against the mutual attraction of these opposite accumulating charges, until the electrical attraction becomes so great that a dart of electrons is shot from one charge to the other. This dart causes the violent breakdown of the insulating properties of the air along a discharge channel, down which the separated charges can now rush freely to reunite. This rush of current generates light, heat, and sound, and also sends out wireless waves, longer than light and " heat " waves, which are heard in our broadcast receivers as atmospherics. These atmospherics, wireless signals radiated from a giant lightning-flash aerial half a mile or more high, and carrying currents of half a million amperes, remain strong enough at great distances from their source to disturb listening ; it has been proved that a lightning flash four thousand miles away in the Doldrums disturbed reception of a Daventry programme by a listener in Bergen, and of a London programme by a listener in Windsor.

At the beginning of this chapter we spoke of a more refined stone-throwing from outside the house than the meteor bombardment of which we are to speak in a still later chapter. This

refined stone-throwing was the apparent bombardment by high-speed electrons in the form of " cosmic rays " which has been the subject of very close investigation in the last few years. Meanwhile, however, we are still so much in ignorance of their relations with the processes of the Weather House that while they should not escape mention they do not demand discussion ; they are a still obscure item in the electricity supply.

Almost equally obscure, though known for much longer by their effects, are still other disturbers of the normal state of the electricity system, the material particles which are shot at the Weather House from spots on the sun. We must be careful about this ; not from sunspots, but from spots on the sun. The results of this sharp-shooting are, however, most obvious at the tenth storey, and so we shall leave this examination until we have climbed, in Chapter XIX, to the ionosphere, the mirror hall of the Weather House. There we shall find that the juxtaposition of mirrors and projectiles is not so ominous as it sounds.

XIII

THE PICTURE GALLERY—OLD MASTERS

In the first dozen chapters of this book we have made a quick and superficial inventory of the aerial furnishings of this ground floor in which we live. In this present chapter we will look at the pictures of these meteorological processes which were drawn by the "old masters" of meteorology, those who, from about the middle of last century to the time of the war of 1914-18 were trying to read the riddle of the weather, with the hope of proceeding from understanding to prediction. Then we shall look in the following chapter at the new methods of painting which came with and after the war; we shall consider how far we still are from understanding the weather of yesterday, how doubly far from any certain prediction of the weather of to-morrow. Later we shall look upstairs, for there may lie some of the missing clues in this tale of mystery and imagination.

We shall pay no attention to the early primitives in this tour of the picture gallery, for their

method was not predominantly pictorial. Edmund Halley did, in 1688, publish the earliest weather map known to us, a diagram of the trade winds and monsoons, but it was not till the Great Exhibition of 1851 that a map showing the simultaneous readings of weather elements at various places was published. The electric telegraph was, indeed, the parent of modern meteorology.

There evolved very rapidly from the earliest maps, representing the state of the weather at the same time at different places, a standardized system of representation which is familiar to the newspaper reader of to-day. The weather map usually shows, on an outline chart, or, better, on a contour chart of the geographical features, a group of figures and letters, with one or two pictorial symbols, placed against each of the dots showing the positions of weather reporting stations. These symbols tell shortly the state of the weather at that particular place at an hour which is, as far as possible, the same for all the places considered. For most European stations the observations are made at 0100, 0700, 1300, and 1800 (1 a.m., 7 a.m., 1 p.m., and 6 p.m.) daily. The most important element recorded in this way is the height of the barometer, measuring,

as we have seen, the weight of the whole column of air standing on a unit area of the observing station. Since the stations are at different heights above sea level the column of air over a hill station will be less tall and less heavy than that over a sea-level station just alongside it, and the difference will depend on the weight of the stuff of which, for the time being, the column is made. It will, then, depend on the temperature of the air. In order to simplify the comparison of these "pressure" readings, then, they are all "reduced" before being written on the map, to the reading which would have been shown by an imaginary barometer at sea level, vertically below or above the real barometer, on the assumption that the bit of the column replaced by the ground, or the extra bit of the column standing in the hollow below sea level, was at the same temperature as that read by the actual thermometer attached to the actual barometer.

The next most important element in drawing this kind of picture is the direction of the wind, along with its "strength," the rate of travel of the wind in miles per hour, lumped, for compactness, into a shortened scale on which 0 represents calm, 3 a gentle breeze of about 10 miles per hour, 6 a strong breeze of about 27

miles per hour, 9 a strong gale of 50 miles per hour, 12 a hurricane over 75 miles per hour. The direction is shown by an arrow shaft travelling with the wind into the observing station, and the strength code (the Beaufort number), by the number of barbs on the arrow. The other elements written in figures are usually the change of barometric height in the last three hours—saying in figures by how much "the glass" is "rising" or "falling"—the temperature of the air at four feet above ground, read with the precautions we have already found necessary to prevent falsification by the thermometer acting as a wireless receiver and transmitter, and the distance, again in a shorthand code, at which known landmarks can be seen, the range of visibility. In letters, or in mixed letters and figures, or (in the most modern of the old masters) all in figures, are added the "state of the weather," the kind and amount of cloud and its height, and whether it is raining or fair or fine, or thundery or misty or foggy, and so on. The same kind of information for the weather since the last fixed observing hour may also be given. In the very best masters there will be still more figures about the winds up aloft, where the disturbances of strength and direction due to the surroundings

of the observing station, and due to the friction of flow over the ground, have been smoothed out.

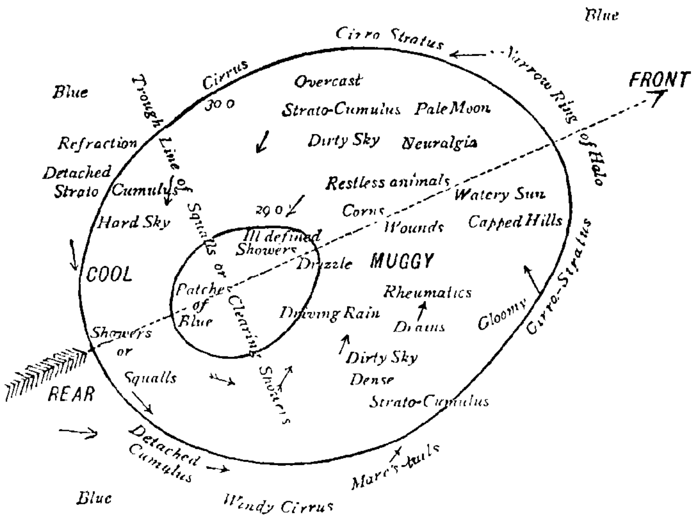
This, then, is the raw material of the picture. The artist then adds some more imaginative elements. Believing that he can infer, from the barometer readings shown, or, more strictly, from the imaginary "sea-level" barometer readings shown, what a barometer at sea level would have read anywhere between the reporting stations, he draws a line through all the places on the map which have the same weight of air above them, one line through all the places where the barometer reads 1000 millibars (representing a load of about a ton of air per square foot), another through all reading 1005, another through all the 995's, one through all the 990's, and so on. These lines of equal load, of equal pressure, he calls isobars, and he finds from experience that they most frequently form families of irregular closed curves, one inside the other, surrounding centres where the load of air is least, or where it is greatest, for a considerable area.

The family of closed curves around a place of low air-weight, of low pressure, of low barometric height, represents the weather system once called a cyclone, then called a de-

pression, now, a little squeamishly and mincingly, called a disturbance or a low-pressure system. In America it is called a "Low", just so. The other family, surrounding a place of heavy loading, of high barometer, is called an "anticyclone", or "High". The importance of these pictures is that, although they never reappear exactly—no weather map has ever been exactly like any weather map drawn in the whole history of weather maps—yet they do fall into groups of family portraits, with strong resemblances among all the "Lows", strong resemblances of quite other quality among all the "Highs". There is, of course, also an infinite variety of intermediate types, but even these can be sorted out into members of a few typical families.

The inspiration and guiding hope of the earliest masters was that a "Low" or a "High" thus delineated would have the family characteristics well developed, and would travel across the country without much change of characteristics. They hoped that the preferred tracks followed by these comparatively unchanging systems could be discovered by sustained study, and that their speeds of travel might be estimated. Thus, having drawn a type portrait of a depression,

with its isobars, its wind directions, its associated weather, and its "prognostics", they might be able to proceed from to-day's map, showing where this complex of weather stood at 7 a.m., to a prediction of where the same complex would stand at 7 a.m. to-morrow. We may imagine their saying to themselves something like this. "This is the true picture of the soul of a depression, and this is the weather you get in different parts of a depression. This picture, by the Hon. Ralph Abercromby (*pinxit* 1883) shows the essence of things. And unless we are very unlucky this depression with its load of weather will move along a track that we shall learn to estimate in advance. So we shall be able to say just when the cirro-stratus in front, with its halos, will come over London, just when the watery sun will confirm this warning of rain to come, just when the dirty sky will give way to driving rain, just when the barometer will take an upward turn, the first streak of blue sky appear in the far west, the muggy air get drier and cooler, the steady rain give place to sharp squall showers and bright intervals." "And," they added, being optimists by nature, if depressionists by calling, "if we are really lucky we may find these depressions showing themselves in New York, travelling, at



To face p. 88]

ABERCROMBY'S PICTURE OF A DEPRESSION (*see p. 88*)

a rate we may learn, across the Atlantic, and arriving to time-table here in Europe." The words are ours, but the ideas are theirs.

The improvement in rapid communication by land-line telegraph and telephone, by marine cable, and by wireless links, greatly improved the quality, the scope, the early availability, and the utility of maps of this kind, and they still form the official basis of weather reporting and forecasting in many countries. But a new school of artist appeared in the early years of the present century and the interruption, in the war of 1914-18, of those electrical communications which had made the older meteorology possible proved to be a new benefaction, for it inspired the modern school, whom I have called the Frontists, to develop a new technique to replace the Vorticist technique of the old masters. When the restoration and further improvement of communications came, Vorticist and Frontist were able to share studios, and the art of weather prediction made notable, if not yet satisfying, advances.

XIV

THE PICTURE GALLERY—MODERNS

WE have seen that the Old Masters, with a characteristically Victorian affection for the flowing curve, produced weather maps whose main features were the nests of oval isobars delineating cyclones and anticyclones; in their scale of values pressure assumed a dominant place. It would be a profitless task to pursue an enquiry into the problem of the relative importance of pressure distribution and air motion; they are no more separable into major and minor roles than are the truth and beauty of other art schools. But a new vigour was brought into weather science by the revolt of a very eminent Victorian, Sir Napier Shaw, who, with his assistant, Mr. Lempfert, showed in 1906 that the vorticist swirl of the isobars in an old master must not be taken to suggest a corresponding vorticist swirl of actual air-packets round a centre, the travelling depression was not a mild and extensive whirlwind sweeping across a continent. Shaw and Lempfert traced "The Life History of Surface Air Currents" in a number of specimen cases;

they traced the successive positions of selected packages of air from hour to hour, from day to day ; they built up " the run of the wind " for some days at a time. And the resulting picture was triumphantly cubist in form, it showed a long straight current of air cutting at a sharp angle into the side of another straight current.

The Norwegian meteorologists, finding themselves cut off by war conditions from the normal inflow of weather reports from many other countries, on which weather prediction in any one country had come to depend, turned to a closer scrutiny of their own local data. From the brilliantly imaginative handling of this limited material grew a new school of weather painting. It was appropriate to the time that the innovators should find their similes in military language, and so this Norwegian school, whom I have called the Frontists, introduced a new language of Polar Front, Cold Front, Warm Front, Warm Sector, and so on. Their pictures are battle pictures, they represent the main happenings in the ground floor of the Weather House as a sustained and fluctuating conflict between cold air and warm air. For them the depression is a salient in a far-flung battle line. The Polar Front of Nor-

wegian meteorology is a line which, over the north Atlantic, at least, runs roughly north-east and south-west, and divides a great polar cap of cold polar air on the north side of the Front from the mass of relatively warm, relatively moisture-laden tropical air which lies south of the Front. For reasons which are implicit in what we have said in Chapter X the cold air north of the Front is flowing from the north-east, the warm moist air is flowing from the south-west. Racial characteristics, opposite trends, are there in sharp contrast ; there are the makings of a fight. This sharp contrast on two sides of a *Front*, instead of a gradual shading-off from pole to equator, is the essential feature of the new, as opposed to the old ideas. Somewhere out in the Atlantic, for no particular reason that we can identify, at no particular moment that we can predict, the warm south-west current makes an apparently unprovoked attack. It swings just a little to the left, elbowing the cold air which was streaming peacefully towards the south-west. This cold air swings round a little to the left also, behind the attacking warm, and so a marked kink in the line is formed. That kink is the kernel of a depression. We have been looking at it on a continental scale ; let us examine it more closely now. A

wedge of warm moist air has been driven into the solid current of dry cold air, the dry cold air has made a large change of direction, it has swung round on the rear flank of the wedge, and is now counter-attacking from that side. But here are two fronts at which marked air convergence is taking place. The front of the attacking warm and light air must rise over the stolid, heavy polar air ; forced ascent means forced expansion, forced expansion means forced cooling, forced cooling of moist air means condensation, cloud, and ultimately rain at this Warm Front, the Front where warm air is advancing over cold. On the Front of the counter-attack, usually lying west of the Warm Front, the cold air is the attacker ; it is moving faster than the warm, being also heavier it drives in under the warm, the warm is lifted up, again we have forced cooling and condensation, this time at the Cold Front where polar air is the active aggressor.

You must not picture the warm air being rushed up steeply in these processes. It does not usually go up by express lift. In fact, at the Warm Front, it goes up the cloud staircase at a very flat angle ; it climbs a mile upward in about a hundred miles of forward travel towards the east. Now we can see how the

cloud staircase presents itself on the approach of a depression. The surface dividing the rising warm, moist air from the cold air beneath it is a very gentle ramp, and the whole system advances on us usually from the west or south-west. So there comes first over our heads, some hundreds of miles ahead of the centre of the depression, the cirrus and cirro-stratus of the top landing, with their solar or lunar halos, later the alto-stratus with the "watery sun" appearance, then the nimbus or nimbo-stratus, low on the staircase, and therefore comparatively near the centre. Rain falls from the hundred miles or so of nimbus in front of the Warm Front itself. Then, as the Front passes us, we get into the characteristic warm, moist, cloudy equatorial air, which, however, is not itself very rainy, because there is not much ascent. Later comes the Cold Front, where ascent is much steeper than at the Warm Front, where indeed we do get the lift clouds, cumulus and cumulo-nimbus, because of the sharp upward heave of the warm air tossed aloft by the attacking cold. The passage over us of the Cold Front is thus marked by a sudden drop of temperature (as the air in which we are bathed changes from air from the sunny south to air from the frozen

north), by a sharp change of wind, and by sharp, heavy squall showers.

The problem of the forecaster, in relation to bad weather, then, is to detect the first symptoms of this advancing battle scene, to estimate how fast it is coming towards us, and along what line, and how the fortunes of war will change the relative positions and vigour of the combatants. It is our fate, for good or ill, to live in the meteorological cockpit of Europe; the front line swings now north, now south of us, sometimes bending back on itself, and these vagaries must be foreseen by the successful forecaster.

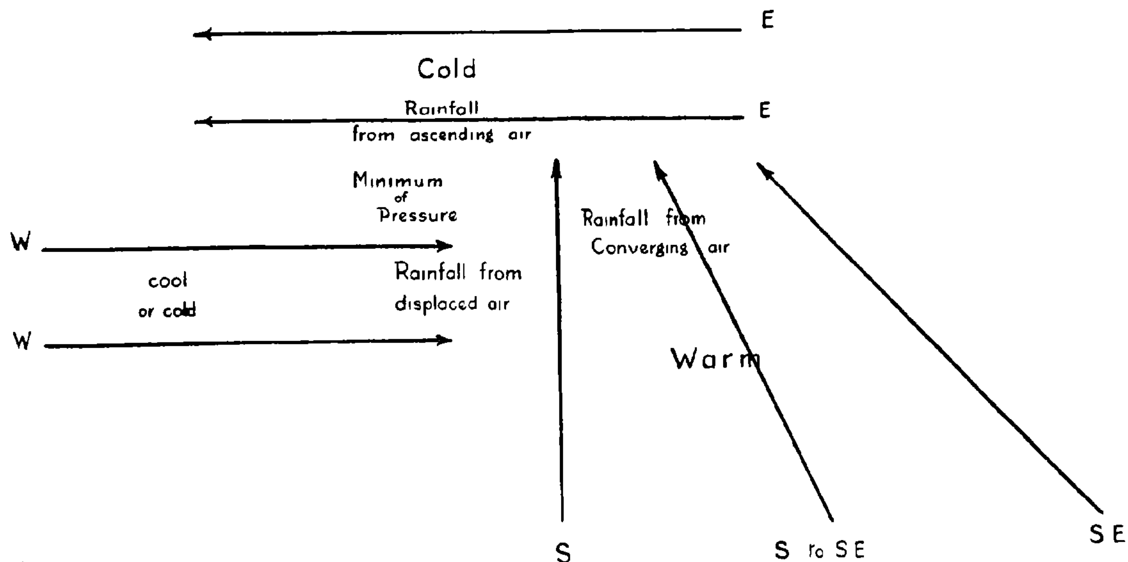
This simple and direct picture, like all the pictures in the meteorological gallery, requires elaboration and modification. There are great variations from simple type, and there is scope for new development along the lines of to-day, in which the working artist uses a mixed technique of Vorticism and Frontism, in proportions which vary according to his personal predilections.

It may be useful to illustrate the Frontist method by applying it to some outstanding features of the weather in one particular week in February when the talks on which this book is based were being broadcast. The actual

wording of one of the talks may, in fact, be quoted.

"We are too often told that we spend our lives crawling about at the bottom of an ocean of air. It is the great merit of the Norwegians that they have an improved version of that story : they make us crawl about at the bottom of rivers of air. These rivers rather tend to keep themselves to themselves, but they change their courses, so that at one time we are in a river flowing from Polar regions, at another in one from the Tropics. And the air rivers remember their sources ; they are cold and clear and dry if they come straight from the Arctic, warm and moist and cloudy, if they come from the Tropics. When they come into conflict we get a depression, a disturbance, a low-pressure system.

"Last week at this time Dundee was having weather very like that of Dungeness—both had northerly winds, yet both were quite warm. Why this ? Both were bathed in the same river of air, no battle-fronts were about, so they were similarly situated. But why warm in a north wind ? Because that wind was a river that had made a tremendous bend in its course. The air had come from the Tropics, over the Atlantic, as a mild south-west current ; it kept



To face p 96]

CUBISM IN THE WEATHER MAP: THE SHAVIAN REVOLT AGAINST VORTICISM (*see p 90*)

warm because it flowed almost along the Gulf Stream, so that it hadn't to give up heat to the water; it picked up moisture as it flowed over the ocean. But when it got to Iceland this river turned eastward, then southward, round a high-pressure area off Ireland, of which you have heard as an anticyclone in the week's weather reports. So the air came really from the Tropics, warm and moist, but pretended to come from the poles by making itself into a north wind quite late in its flow.

" I don't know if you had heard that Spain had a fine warm day last Wednesday, but towards evening there the wind went a little east of north, after having been more westerly. We shall see shortly what that meant. About midnight on Wednesday evening a new river of colder air flowing down from Norway got into argument with the warm river and produced squall showers over Scotland. This illustrates something I said last week. The moisture which it picked up from the Atlantic was all there in the river of tropical air; but it didn't come down as rain until a colder current cut underneath the warm moist air and forced that upwards.

" By seven on Thursday morning cold air from the wintry continent of Europe was flow-

ing as a river of north-north-easterly wind over the Dungeness area. Dundee was still in the warm river, and Iceland—in the same tropical stream—was actually the warmest place in Europe then. It showed 54° F., while Morocco was very nearly freezing.

" Midday on Thursday found Dundee still 44° F. in the Atlantic air, Dungeness at 38° F. in the Scandinavian air, which was, however, somewhat tempered by heat stolen from the heat-storage tank of the North Sea. This Scandinavian river was now flowing fast, giving a north-easterly gale at Yarmouth. Thursday evening showed Iceland still at 55° F. Dundee had had a fine day without much cloud because the warm river was not merely flowing on, it was broadening. There was air divergence at the surface, so more air was coming down from aloft.

" You know that rising moist air means cloud and rain, but the opposite also holds : descending air is heated by compression and is, therefore, getting drier, so it ' mops up ' clouds, and leaves blue sky. Dungeness was shivering in its cold air at a little above freezing point in a strong north-easter. And as for the Sunny South, the Rhone valley had snow and five or eight degrees of frost.

" On Friday Spain was in a river which had followed another rather misleading course. After flowing over the snow-covered lands of Central and Eastern Europe—a very effective cold-storage tank—this river of refrigerated air turned westward somewhere in the Balkans, ran along by the snowy Alps, and poured over shivering Spain. There was an incidental example of how good the tempering influence of the sea can be. Bordeaux was also in the cold air ; a ship only a hundred miles out in the Bay got the same air, but heated by 10° F. on that short sea route.

" Coming back to Britain we find the Midlands having fog and drizzle at midday on Friday, because the wedge of warm air still covering the northern districts was there mixing gently with the cold air that covered the south ; Dungeness was down below freezing in the early evening. But it wasn't exceptionally uncomfortable. Nice was freezing, and a snowy mistral was blowing down the Rhone valley.

" I don't know if any of you remember last Saturday in London. I used on it all the adjectives I had left over from the fog of the Wednesday before. The battle-front, where the warm moist air (which still covered Scotland with a blanket of cloud) was climbing over the cold

air of the south, was now practically over London ; the fight gave drizzle and fog, but the cold air added the joy of a nearly freezing temperature. Was it a comfort to know that the Riviera had a 50-mile-an-hour gale, and 30° F.?

" Sunday we shall call a *dies non* for present purposes. On Monday morning Dundee had lost its cloud blanket by the ' descending air ' process which I have just mentioned ; it had blue sky ; it indulged, Scotch as it was, in an orgy of spendthrift radiation, and got down near freezing. By noon a new surge of warm air north of Scotland threatened a repetition of the events which had led up to Saturday's weather, but the forecasters decided, correctly, that it would not travel south.

" And the last events of the week which I have to account for are the changes which made yesterday in London the first day of spring, with a slight relapse to-day. I needn't really explain, because yesterday's blue sky was another product of the descending air which had given Dundee some blue sky on Monday. The best evidence of this descending air was the aeroplane observation of extremely warm and extremely dry air—50 degrees, and 21 per cent relative humidity at 3500 feet, as against

31 degrees and 95 per cent relative humidity at the ground.

"And to-day that very persistent river of warm moist air from the Atlantic was again in charge of eastern districts, and its descent was clearing the sky in the evening. May I add that this morning round Paris was calm and serene above with radiation fog below?"

XV

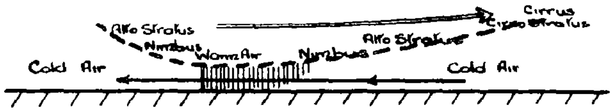
THE GROUND-FLOOR CEILING

We can still make personally conducted tours above the top of the cloud staircase, for, as you will remember, the altitude record for aeroplanes is nine miles, and the stratosphere tourists can go still higher. And if we watch our thermometer carefully after we leave the cirrus level we shall find that it has ceased to fall, that it even rose a little, and that now, from about six miles up, it has hardly moved. It is not, of course, very often that we can go to these levels to read the thermometer personally, but the *ballon sonde* brings us frequent messages from these levels, and the messages all show that at a height, over Europe, of about six miles the comparative steady drop of temperature with increasing height ceases, and there is very little temperature change in the next six miles of climbing, in going from ground-floor ceiling to first-floor ceiling, if we fix the height of each storey, as we agreed to do, at six miles. This six-mile height is suggested, in fact, by the height at which the extremely important change from a steadily

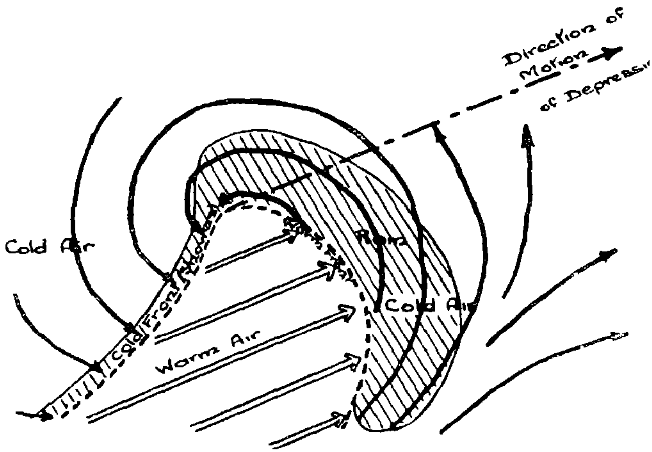
decreasing temperature, as we climb, to a steady temperature takes place. It is Nature's marking off of the ground-floor ceiling.

That there should be this rather mysterious invisible ceiling can be explained by going back to the bookkeeping of radiation exchange. We have to think of the debit and credit sides of the radiation ledger for any particular slice of the atmosphere. There are two ways, as we have seen, in which heat is redistributed between this slice and its neighbours above and below. There is the action of the slice as a wireless receiver, in which it heats itself by absorbing some of the incoming radiation, and as a wireless transmitter, in which some of its warmth is lost as radiation which goes off upwards and downwards. On the other hand there is the effect of convection, of the invasion of the region by rising air from below or descending air from above, and of its loss of rising air to the slices above and of descending air to the slices below. These travellers do not merely carry their own store of heat as unchanging quantities of luggage, they are constantly gaining and losing heat by the processes of dynamic cooling and heating. Once the ground-floor ceiling was discovered, by actual measurement, the reason for its existence was soon given, although, as

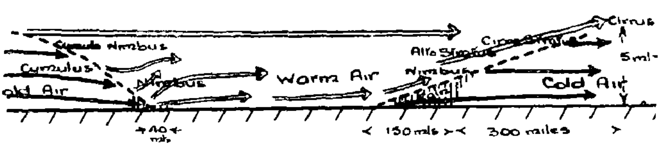
almost everywhere in meteorology, the explanation is incomplete and in broad outline only. It was shown that at a certain level in the atmosphere, depending on the amount of water vapour present, the radiation exchange was in almost complete control, and convection was unable to play any very important part. At lower heights, however, spendthrift radiation was robbing each successive slice of some of its heat store, while the total quantity of radiant energy going downwards through the slice was greater than that going upward through it. This would mean that each slice would go on getting colder than the slice below it. But there would come a time when the process had gone so far that the warmer air in the lower slices would begin to rise, the cooler air above to fall " by its own weight", and the convective processes thus started would bring about the more or less regular fall of the temperature with increase of height that we discussed in Chapters III and IV. The exciting thing about the explanation, when it was brought down to arithmetic, was that the height up to which convection was important, the height above which convection was unable to redistribute the heat by redistributing the air itself, came out very closely in agreement with



Elevation, Section North of Centre



Plan



To face p 104] Elevation, Section South of Centre

THE NORWEGIAN PICTURE OF AIR-FLOW, CLOUD AND F
IN A DEPRESSION (*see p 93*)

the measured height at which the fall of temperature with height ceased. The more water-vapour in the ground-floor, the higher its ceiling, and this is why the ceiling is much higher over the tropics, where the intense heating of the floor, and the consequently higher air temperature, give a greater water-bearing capacity to the air than over temperate and polar latitudes. You will remember here, from Chapter IV, that water-vapour is the "fuel" that enables the otherwise rather feeble upward drive of rising air to push its way to high levels in the ground floor. This it is that indicates how the greater water-bearing capacity of tropical air accounts for the great height of the ceiling over the tropics. Above this ceiling the radiation exchange is all-important; how it works will depend on the qualities of the different floors as wireless receivers, and about that we may say a little in later pages.

We can, by thinking again of the processes of Chapters III and IV, turn our argument of this chapter the other way round, to convince ourselves that this region in which temperature no longer falls as we go up is an insuperable barrier to the rising currents of air. For these must, if they continue to rise, go on being still further cooled by our now familiar dynamic process.

But the air around them is no longer colder as they rise into it ; they are therefore colder than their new neighbours, and will fall back to lower levels where they are again like those around them.

Here, then, where staircase and lifts alike come to a compulsory stop, we pause to take stock of the ground floor and its furnishings, before we go upstairs to look at the rest of the house. Having looked at these upper storeys we may return to our familiar home on the ground floor to talk again about weather-making, but meanwhile we want to fix in our minds the special features of this troposphere of ours. For all its insubstantiality it contains about four thousand billion tons of air, and when we have climbed to its ceiling we have left about three-quarters of the whole weight of the atmosphere below us, the remaining hundreds of storeys weigh just over a thousand billion tons in all, the column of the upper storeys which rests on a square foot of the ground-floor ceiling weighs only some five hundredweight, while the column below it weighs, as we know, the remaining three-quarters of a ton. The weight of water-vapour contained in the ground-floor shell is, on the average, probably about ten billion, certainly

not twenty billion, tons ; it has been assumed, not very securely, that there are less than one billion tons of water-vapour in the whole atmosphere above the tropopause.

The highest air temperature ever recorded at the floor level is 136° F. Here it may be well to remember the distinction between temperatures " in the shade", which have a definite meaning, and " in the sun", which do not. It all turns on our being wireless receivers. When we want to measure the temperature of the air we must make sure that our thermometer itself is not being heated otherwise than by contact with the air around it. If we put a thermometer where the sun shines directly upon it, the thermometer will act as a wireless receiver and be heated up by absorbing radiation from the sun. The amount of heating up will depend on many things, the colour, the polish, the surroundings of the thermometer, and so readings " in the sun " have little meaning. But if we put the thermometer in a well ventilated meat-safe, which the meteorologist calls a " thermometer screen", or if we suck a stream of air sufficiently rapidly past our thermometer bulb, we shall get a true measure of the air temperature. The " record " shade temperature, then, is 136° F. reached at Uzzizia, in Tripoli, on September

13th, 1922, and almost equalled in Death Valley, California, on July 7th, 1913. At the other extreme is the lowest shade reading (and again there is a need to make sure that the thermometer is not cooling itself below air temperature by acting as a too vigorous wireless transmitter of long-wave outward radiation) of —93½° F. at Verkhoïansk in Siberia on January 3rd, 1885. To get the lowest temperature measured anywhere in the bottom storey we must think of the slope of the ground-floor ceiling from being only about four or five miles up above the North Pole to about ten or eleven miles above the Equator ; this brings us to the slightly paradoxical fact that the lowest temperature ever measured was over the Equator —131½° F. at ten miles up above Batavia on December 4th, 1913. Thus the highest and lowest temperatures measured anywhere in the Weather House are easily remembered as being about +132° and —132° F. respectively ; the freezing point of +32° F. is a reminder of the tens and units figures, near enough for all practical ends.

XVI

THE FIRST FLOOR

THE main characteristic of the first floor of the Weather House, is as we have seen, the somewhat singular behaviour of the central heating installation. A little information about other things there has been brought back by the stratosphere explorers, and some of that information is nearly as unexpected as was the earlier discovery of the tropopause, the ground-floor ceiling. The stratospheric balloon manned by the Soviet explorers Prokofieff, Godunoff and Birnbaum reached a height of nearly twelve miles, nearly, that is to say, to the first-floor ceiling, although we have not yet found a reason for expecting a real ceiling at twelve miles as we did at six. The lowest temperature experienced by these pioneers was —70° F., illustrating again the cessation of the chilling process as we go upwards.

The electrical measurements made by the explorers are of great interest, but one of their most interesting results was one on a more familiar plane than that of electrification. They took up sealed globes of glass which were care-

fully cleaned out, emptied—as nearly as possible—of all air, and hung outside the gondola, with precautions against air or gases from the balloon itself getting in when, at length, it was desired to take a sample of air from the first floor levels. The samples were taken only when the balloon was floating or descending gently, and the opening and resealing were done electrically. The samples were carefully analysed by two independent laboratories. The air was found to be practically identical with that found near the ground, save that it was " bone dry". This identity is a somewhat surprising result, and to see why it is surprising we must consider what would have been expected had the experiment been tried a dozen years earlier. We know that the air at the levels where we live amongst it, here on the floor of the Weather House, is a complex mixture of different gases, but with two ingredients in overwhelmingly greater proportion than the others. Oxygen, the " staff of life " of the gaseous world, forms 21 per cent by bulk of the mixture which we call dry atmospheric air. Nitrogen, the diluent which keeps us from burning up too fiercely on our indraughts of oxygen, but which has a more positive role in the feeding of plants, forms nearly the whole of

the remaining 79 per cent. But there are traces, important though small, of other gases, totalling about 1 per cent, so that nitrogen is nearer 78 than 79 per cent. The argon which is now used in our gas-filled electric lamps is the most copious of these residual ingredients, then comes hydrogen, about .1 per cent only, then the neon of the flashing signs, the helium of the non-inflammable airship, the krypton and the xenon which have scarcely yet been pressed into the service of man. Carbonic acid gas and ammonia are there in amounts which vary considerably according to the circumstances controlled by the living things on the earth's surface. And in the far from desiccated air which furnishes the Weather House there is, on the average of the whole world, just over 1 per cent of water-vapour—when the sample is taken at ground level.

Now on the older ideas about how these gases might sort themselves out by their differences in weight, in a region where the evenness of temperature suggested that there was little air motion, and the ingredients were no longer kept well mixed by the stirring of the convective process, the sample taken at twelve miles up ought to have been very different. Oxygen should have been much less prominent, though

still the second ingredient. Roughly we might have expected to find one of oxygen to six of nitrogen, instead of one to four as at the ground. It is true that these too-simple theories had been shaken before the ascent of "Stratostat U.S.S.R.", but this evidence was more convincing than any other. Was it, however, certain that the glass globes had not, by some unfortunate accident, been allowed to fill with air from the ground level? There were two tests. One was to measure what the pressure inside the balloons would have been at —70° F. It appeared that the weight of air above the balloons when they were filled had been only a hundredweight and a quarter instead of a ton per square foot as at the ground. So this filling had almost certainly been done well upstairs in the Weather House, with the great bulk of the fabric below the filling station. But there was one conclusive test. Surface air was bound to contain something like 1 per cent of water-vapour. The samples in the balloons had so little that it could not be detected, though the methods used would have detected .04 per cent. The air was the characteristically dry air of the stratospheric first floor, not the moist air of the tropospheric ground floor. Characteristically dry, because the tropopause,

the ground-floor ceiling is, as we have seen, almost as effective a barrier for the upward passage of water-vapour as if it were a concrete ceiling, and, because the cold air of the stratosphere can hardly carry more than an infinitesimal burden of water-vapour in any case, air at that level, and at —70° F. would be saturated with a few thousandths of an ounce of the water vapour ingredient to a pound of air.

There is, then, proof that although the considerable wind speeds which we shall find in the higher storeys (Chapter XVIII) can hardly fail to have their counterparts in this first floor, and although the thorough mixing of the constituents of air at this level confirms this expectation, yet the wireless exchange of heat programmes in this storey is so vigorous as to outbalance the tendency towards the fall of temperature with height which we have learned to expect in a well-mixed atmosphere. The temperature levelling effect of a vigorous exchange by radiation wins over the apparently less vigorous mechanical mixing, and the uniformity of temperature with height is our evidence of this victory of wireless over winds.

It must not be assumed that this steadiness of temperature with height means also a steadiness of temperature with time. The tempera-

ture of the first floor, and with it the height of its floor, changes from season to season, and indeed from day to day by quite considerable amounts. The comparatively smooth hour to hour variation which we experience at floor level, and which, as we saw in our earliest chapters, is due to the action of the floor itself, does not extend very far up even in the ground-floor region. That this is so, and that nothing of the sort is found in the first floor, was most convincingly shown in two epoch-making experiments at Manchester, in each of which twenty-five *ballons sondes* were released at hourly intervals to bring back messages as to the march of events throughout a whole day.

That, meanwhile, is almost all we know about the first floor and its furnishings. It is a dry territory, cold, but equably cold, apparently cloudless, with more than three-quarters of the weight of the Weather House below it, itself comprising about a seventh of the whole weight of the house, with only a residual sixteenth above it in the tenuous hundred storeys aloft. What a stratospheric skyscape is like we shall realise when we talk about the lighting system of the Weather House as a whole.

We shall not be able to discuss every storey of the Weather House in detail, not because

there are a hundred storeys, but because we should have to build our house without bricks ; we know so little about many of the storeys that we cannot say much until we learn more. For that reason we shall say something about messages from the lower part of the second storey, from the middle of the fourth storey, and a good deal about the ninth, tenth, and " twenty-somethingth " storeys. The rest is fragmentary.

XVII

THROWING STONES AT THE WEATHER HOUSE

AND now, finally, we have passed beyond the range of direct exploration ; the first-floor ceiling has, for the present at least, proved to be the ceiling of manned flight. Our news from above must now be brought to us by less substantial messengers than our fellow men. Of all these messengers the light wave, that particular kind of wireless wave for which our eye is a ready-tuned receiver, is the most informative. But since the thermometer has told us much about the two lowest storeys we ask first what the thermometer says about the second-floor furnishings. The mercury thermometer froze, it and the spirit thermometer alike require too many accessories to give us a written message from above, the story must now come back in cypher, scratched on a tiny plate of silver or celluloid, carried in the spidery framework of the *ballon sonde* recorder, the meteorograph. The most generally used balloon meteorograph, a marvel of instrumental ingenuity, has a tiny aneroid barometer which

moves the silver plate sideways by amounts proportioned to the atmospheric pressure while a needle of the bimetallic thermometer scratches a line downwards in proportion to the temperature. You notice that the cypher message says nothing directly about height, it is merely a microscopic graph, of postage stamp size, of temperature plotted against pressure. From these two factors the actual height is readily worked out, although it is, indeed, of less importance than the combination of temperature and pressure from which it is inferred.

The greatest height sounded by this messenger is not vastly higher than that reached by Stratostat U.S.S.R. A *ballon sonde* rose to 22½ miles above Hamburg, so that the *ballon sonde* has taken us just twice as far as the manned balloon. But the most interesting evidence which it has brought us is from levels just above those so recently visited by man in person. In the last year records made by Belgian *ballons sondes* showed a feature not previously interpreted with any degree of certainty. About halfway up in the second floor the thermometer, which fell steadily in the ground floor, and kept steady in the first floor and in the lower reaches of the second floor, began to rise again. And on that rise hangs part of a detective story in which

the first clue in a tangled plot was found on the fifth floor. It hung on the tale of a meteoric career.

It had long been known that "shooting stars", "falling stars" or meteors, were fragments of solid matter entering the atmosphere from outside ; meteor showers resulted from a celestial game of throwing stones at the Weather House—or throwing the Weather House at stones, which comes to the same thing. Specimens of these celestial missiles may be seen in any well-found museum, and they tell us something about the building of other houses than our own. The size of the missiles varies enormously, the majority are, fortunately, about the size of a pinhead, the largest specimen whose effects have been studied weighed about 130 tons. This giant fell in a—happily uninhabited—part of Siberia, on June 30th, 1908, and devastated an area as big as Yorkshire ; not a tree was left standing, and they all fell outwards from the centre of the colossal impact. But that, and the exceptionally bright nights which followed, and the air waves which travelled round the world with a message which was not deciphered till many years later, is a different story in itself.

These visitors from abroad flare up into in-

candescence because of the heat generated as they rub their way through the resistant though rarefied air aloft, at a speed of about 25 miles *per second.* The heights at which they most frequently appeared and disappeared had been studied—are still being studied—by professional and amateur observers. They usually appear in the tenth floor and disappear in the eighth, or, less often, the fourth. Just ten years ago two distinguished workers at Oxford pointed out that these heights, along with the other known facts about meteors and their ways, suggested that the air above 30 miles up, the air above the fifth floor region, was much warmer than had been supposed, much warmer than the air in the first floor region. It seemed probable, in fact, that the thermometer in some of the higher floors stood at a snug +80° F. and not at a Spartan—70° F. or below. But the language of the foreign gate-crashers was not perfectly understood. Could we not send messengers of our own to confirm or correct our reading of their evidence? Not men, not *ballons sondes*, for we must get higher than they had yet gone. True, shells from "Big Bertha" had been nearly far enough, but they were undocile spies. Yet these shells had close, if invisible, relatives who would serve. For big

guns fire not merely shells but sound waves, and much was already known about the hearing, in London, for example, of gunfire from the Western Front, 1914-18 ; it was known that gunfire at Portland might startle ponies in South Wales, though it was inaudible in Devon. The sound waves from explosions showed the peculiarities—later shown by short wireless waves—that they could be picked up anywhere in an area immediately surrounding their place of origin, that outside this area there was a zone of silence, a skipped zone in which they could not be perceived, but that outside that zone they could again be picked up. The most plausible explanation for both cases, the air waves of sound, and the ether waves of wireless, was that somehow the waves were being turned earthward again after they had gone aloft in the Weather House. The wireless waves we shall meet again, let us think now only of the sound waves. Sound travels faster through warm air than through cold air, and this results in the bending of sound waves when they travel through air strata of different temperatures. The time-worn illustration of this bending process is still satisfying, and no apologies need be offered for using it here. A party of soldiers is advancing across country in line abreast. So

long as each man is marching at the same speed as all the others the line maintains its direction, the line of march is straight and at right angles to the line of men. If they now want to wheel right, how can this be neatly done? By the man on the extreme right slowing down a little, the next man slowing down, but not so much, the man on the extreme left going on at his original rate. This will wheel the line so that the new line of march has turned a little towards the flank on which the slowing began. Now the slowing down may be imposed by the nature of the country. Suppose the line is approaching the boundary between a pasture field and a ploughed field, and that the boundary is sloping across the line of march, so that the right-hand man reaches it first. He steps over the boundary into heavy going, and is slowed down. His left-hand neighbour reaches the boundary one pace later, and is slowed down later, so he has gone on ahead. Thus the slowing down goes down the line, and when the extreme left-hand man has crossed the boundary the whole line is advancing again, on a perfectly straight front, in a perfectly straight line, but no longer in the original straight line, for they have wheeled right. If, instead of the sharp boundary, there had been

a gradual softening of the ground the line of march would be curved so long as the nature of the ground was affecting the right-hand and left-hand ends of the line differently. If on the other hand the right-hand man comes out first on to easier ground the line will swing towards the left. Always, then, the effect is for the line of men to swing more nearly parallel to the boundary between regions of unequally easy going, that is for the line of march to bend inwards towards the region of lowest marching speed.

The sound waves from an explosion, travelling obliquely up into an atmosphere which consists of successive horizontal slices each at a successively lower temperature, behave in the same way. The bit of the " wave-front " which is highest up travels ever more slowly, because it first takes up the lower speed due to the lower temperature, the sound-ray bends ever more steeply upwards ; in the troposphere, on the average, with its steady fall of temperature with height, sound rays are bent more and more away from the earth. In the stratosphere, on the average, with temperature no longer changing with height, the rays go on in the direction which they had as they passed the tropopause. But that the rays turn towards earth again

suggests that somewhere above the stratosphere they have come into a region where they travel faster above than below, where, that is, the temperature increases again with height. There the ray bends to become less steep, then for a moment to travel horizontally, and after it has got past the horizontal it comes down to earth again.

The general experience is that an explosion is heard everywhere within twenty or thirty miles, is unheard beyond this radius, and is heard again beyond eighty miles. Observations in England and Germany alike indicate temperatures of about $+130°$ F. at the fourth-floor level.

The sound of a gun fired at Woolwich, then, may bring to Birmingham and Bristol the message, which can be deciphered in real figures, that the air waves carrying the sound have been up to the fourth floor and have found there a temperature much higher than in the intermediate floors. In fact they agree in telling the same story as that suggested by the meteors, of temperatures there which would be very high summer temperatures at ground level, and which are greatly above the freezing temperatures found in the region below the ground-floor ceiling. Why?

XVIII

HOW THE FOURTH-FLOOR TENANT MOVED DOWNSTAIRS

THE temperature at the fourth-floor level is, as we decided in Chapter XV, governed by the radiation balance sheet. If it is as hot as we find the meteors and the sound waves saying, there must be a very good wireless receiver thereabout turning some bit of the solar programme into warmth. And the bit that is turned into warmth up there disappears from the programme as it reaches us in the ground floor. Here is hope of a new clue, can we pick holes in the wireless programme?

The clue is only of value if we know what wavelengths are sent out from the solar transmitter. If we do, we know—by finding which of them reach us at the floor level—which of them have been intercepted in the upper storeys, and we may even be able to decide who was the tenant who intercepted them. Since, however, we cannot reach the floors at which the interception is taking place, we can only infer what the original programme was like. The work of a large number of detectives,

following up very different lines of investigation, combine to make it very probable that the solar wireless transmitter is sending out wavelengths shorter than the shortest ultra-violet wavelengths which reach us at the ground floor, and that the sharp boundary between the shortest we do receive and the longest of those we do not receive is due to interception by an otherwise unobtrusive upstairs tenant called ozone, a very close relative of the oxygen which we have found on the ground and first floors, and which we shall find again in the tenth and hundredth storeys.

The whole of the ozone in the Weather House, if it were collected into a pool covering the whole floor of the House, would be only an eighth of an inch deep. Yet it is convicted of converting to its own use a considerable range of the short-wave programme from the sun, and using it to warm itself and the air of the upper storeys of the Weather House. The mis-appropriation, if one may reasonably use the prefix, affects about 5 per cent of the whole supply from the sun and it has had the most profound influence on terrestrial life, for if these short waves had been able to reach the earth's surface they would, at the least, have made us all negroes, at the more probable they

would have made life impossible for the human race as we know it. All things in moderation—even sunburn !

It seemed not unreasonable to infer from the high temperatures apparently existing above the fourth floor that the principal tenant there was ozone, and that the fourth floor was his principal address. The Oxford workers who were concerned with the meteoric evidence made this inference. When they had done so the next step was for other workers to bring out the evidence from the travel of sound waves, and everything seemed to fit together with the snug satisfaction of a well-cut jigsaw puzzle. But 1933 brought a new deal—the metaphor is no more confused than the evidence. The same Oxford group, with co-workers abroad, produced convincing new testimony that the main concentration of ozone was to be found not in the fourth or fifth floor levels, but in the second floor, with a spread over into both first and third floors. And so the almost indubitable facts adduced by the explosionists to support the original theory were left unshaken, but with no original theory to support. The suspected tenant of the fourth floor was found to be living a floor or two lower down, but the fourth floor was still pretty certainly a summer-house.

There the plot of the detective story stands—stands is hardly the word, for it is an ever-developing serial of absorbing interest, to be continued. . . . But meanwhile it takes us back to that other clue which we left in the air of the second floor, for it gives us in the ozone tenancy one possible reason for the rising thermometer of our *ballon sonde.*

The new conclusions about the ozone furnishings are much more definite than the old. They are based, at present, on observations made in Switzerland, and the workers in presenting them say: "The height of the centre of gravity of the ozone can be relied upon to within a kilometre." This height they fix at about fourteen miles up, while they add "the ozone is distributed mainly between the ground and twenty-two miles up". Another important conclusion which they also draw is that the very considerable *variations* in the amount of ozone observed at any particular time appear to take place mainly in the first floor.

Although ozone was the first of the upstairs tenants to be examined about his dealings with the incoming programme this was, in part, because he had well-marked personal characteristics which the detectives could recognize fairly readily. It is now necessary to look at

other tenants in the same sort of way, although direct clues will be very much more difficult to find. Oxygen, for example, is known from a wealth of laboratory experiments to have a *penchant* for stealing still shorter wavelengths in the ultra-violet end of the spectrum, and it seems probable that the high temperatures in the fourth floor and above are due to his central heating system being fed from these parts of the solar regional programme. That he is an important tenant of these upstairs flats is revealed by the auroral draperies which we shall meet in our next chapter.

We shall devote ourselves now to the gathering together of a few other straws which show how the wind blows in these upper storeys. The meteors tell us something about this, for their sideways drift, as they are carried along by the air currents through which they fall, make them invaluable wind gauges. There is something to be found from them about conditions at two different levels. The luminous trails observed at night are generally at heights of about 50 to 75 miles, they lie, then, in the eighth to the twelfth floors. They tell of winds which are strong but variable in direction. By daylight, however, the meteors may be observed to leave trails of smoke, which are seen more frequently

at rather lower levels, in the third to eighth floors in fact. There the winds are mainly from the east. The relation of wind speeds at great heights to the aeroplane speeds of to-day will give us something to help our mental picture, but we ought first to go back to the ground floor to look at comparative wind speeds there.

What we call a gale at the surface is a wind speed of forty miles or over, and there is an unofficial gloss to the Beaufort scale of wind force saying: "Force 12 (hurricane), above 75 miles per hour, will in general be reported from a land station only if observer and observatory have both been blown away." This seventy-five miles an hour is about the highest wind speed reported from the strato-cumulus level, say a mile and a quarter up, while cirrus at about six miles up has been seen to be blown along at 225 miles per hour from the westward. We have, then, evidence of something over two hundred miles an hour from the west in the ground floor; we shall learn in a moment of winds something under two hundred miles an hour from the east in the eighth storey. There is a rarely seen inhabitant of the second floor whose appearance lets us fill another gap in the wind diagram, an inhabitant who, like all the upper-floor tenants, is a still mysterious and,

like most of them, an unusually beautifi creature. Once in a while there appear in th night sky clouds even less rudely robust tha the filmy cirrus, clouds with an exceptionall delicate mother-of-pearl lustre, clouds clearl not belonging at all (perhaps, however, relatec to the ground-floor family, but floating at abor fifteen miles up, halfway between floor an ceiling in the second floor. They seem, fairl certainly, to be made up of water drops—th reason will emerge when we look at th "decorative lighting" section of our Weath House story—but we do not know how wat in sufficient quantity gets there nor how it co denses to cloud. The drift of mother-of-pea clouds does, however, indicate variations fro calm on one occasion to wind speeds of 1 miles per hour on other occasions at these level so that the contrast between the turbule underworld below the tropopause and th serene heights above it must not be taken imply a permanent and featureless calm alo

The last of the cloud fabrics flies as a st rarer banner on the seventh or eighth store of the Weather House. From Berlin in 1884 1901, from Norway and elsewhere in 193 there were observed "luminous night clouds almost formless patches of faint illuminatio

clearly distinguishable from the aurora borealis of which we shall speak again, and sometimes with just enough permanence of feature to enable the rate of drift of some marked element of their pattern to be measured by optical observations from below—by the means which are used for measuring the heights at which the aurora itself appears. These eighth floor banners, too, tell of two hundred mile an hour winds, these blowing from the eastward.

The dust cloud from Krakatoa (1883) may have had a good deal to do with the earlier series of luminous night clouds. More direct observations on the dust in the year of the eruption itself showed an *average* wind of 50 miles per hour from eastward at a height of 50 miles over the equator, again, that is, in this eighth floor.

And so we leave the regions where material and visible labels are to be found attached to any individual piece of the aerial furnishings of the Weather House ; we climb to regions where still more abstract clues have allowed our picture of the higher storeys of the house to be painted with a wealth of detail that cannot be equalled in the sketches of the intermediate floors.

XIX

LA SALLE DES GLACES

IT is a pity that the Weather House has no rea roof, because " radio roof " runs so trippingl off the tongue. But we may at least call th ionosphere the radio ceiling, until we discove that it consists of a number of ceilings, whic are disconcertingly revealing themselves as ou explorations proceed. The ceilings we have dis cussed up to this point have been marked b more or less sudden changes in the behaviou of the thermometer as it got to greater an greater heights. At the ground-floor ceiling th thermomenter steadied after its cooling down at the natural ceiling of the first floor the ther mometer reading began to rise again as w climbed. Whether the radio ceilings are simi larly change-points for the thermometer we d not know ; we shall have to infer the proba bility from purely radiotelegraphic observa tions.

The story of the ionosphere—that region c the upper atmosphere whose most importar characteristic is ionization, or the presence c many free electric charges, the region whic

turns our wireless waves (the waves used in broadcasting and in transoceanic communication) back towards the earth's surface again—begins before the discovery of wireless signalling. The earth behaves as a great magnet, so that the needle of the mariner's compass points towards the north. It does not, however, point as steadfastly as the poets would wish. It points in slightly different directions at midday and at midnight, and there come times when it performs somewhat wild jumps and oscillations, times, in fact, of "magnetic storm". The many perturbations of the magnetic field await explanation in detail, but it was already clear, in 1878, that many of these vagaries could only be explained if there were, in the upper atmosphere, regions in which quite strong electric currents could be made to flow. The magnetic effects of these currents would deflect the compass needle, just as those flowing in the coils of the electrician's galvanometer deflect the compass needle put in it to measure their direction and strength.

When Marconi signalled across the Atlantic it became necessary to explain how his wireless waves surmounted the mountain of water, 140 miles high, which rose above the straight line joining Cornwall to Newfoundland. The sug-

gestion that the wireless waves might be turned back earthward after striking some reflecting surface at a great height was made independently by a number of physicists. Scepticism, however, remained for a long time; a healthy and quite proper scepticism which asked for experimental demonstration on a scale too simple to leave room for alternative explanations. The sceptics were answered only seven years ago, the wireless mirror was demonstrated, but in these seven years the roof-garden of the Weather House has proved itself a veritable *salle des glaces*. The exploration has been done mainly by a kind of echo-sounding which is much more easily understood than are the reports that it provides.

In the not unfamiliar cases of the echo from a hillside or an island cliff-side, and so on, we can measure the distance, between ourselves and the surface that is acting as a mirror for sound, by a crude echo-sounding. We clap our hands and count seconds until the echo handclap reaches our ears. Knowing that sound travels a mile in five seconds we get the distance of the double journey made by the sound if we divide the echo-delay-time by five. Recent improvements in ocean-sounding have been based on the same method. A mechanical handclap

made on shipboard is timed on its travel to and from the ocean bed ; the much higher known speed at which sound travels through sea-water is then used as a factor to give the distance from ship to ocean bed. The distortions undergone by the original sound impulse bring, in addition, some information as to the nature of the bed ; it may even at times report the presence of shoals of fish at intermediate depths.

A wireless handclap is readily made, although it is a very special kind of handclap indeed. It is politely called a pulse of radio-frequency energy, and it is generally something that lasts only about a three-thousandth of a second or less. Such a pulse sent out from a transmitting aerial travels almost exactly a million times as fast as does a sound wave in air, and so it will reach a receiving station a mile away, by travelling along the surface of the ground, in a time so short as makes no matter. We let it make a mark on a paper, and that mark represents, as nearly as need be, the moment when the pulse left the sending aerial. Then we wait, and presently the pulse arrives all over again, and makes a new mark, which we can cunningly contrive to be separated from the first by a distance proportional to the time which

elapsed between the two arrivals. Whence the second comer? The time between the two arrivals is frequently very exactly two three-thousandths of a second. If it is not exactly that it is very seldom indeed anything less, and it is not very frequently anything between this two-thirds of a thousandth of a second and one and a half thousandths of a second. But in fact we find not one echo—for the second arrival is a wireless echo—but many, and when we multiply the time-delay of each by the speed at which wireless waves travel in air which does not contain free electricity (186,000 miles per second) and divide by two, we get the apparent height to which our radio-frequency pulse has climbed before it met a wireless mirror to reflect it back to earth again. It would be tedious to go further into the mechanism of this new echo-sounding, we may proceed now to the message brought back by these insubstantial messengers from the upper floors. First, however, we must discover what a wireless mirror really is. We have already spoken in this chapter of a region in which electric currents can flow freely, and of regions in which the air contained no free electricity. That these are contrasted states will be clear from the argument of Chapter XII, for there

we saw that an electric current is a flow of "free" electric charges, so that air containing no free electricity does not allow electric currents to flow freely. Chapter XII helps us, too, to understand why a region in which electric currents can flow freely is a wireless mirror. Although an electric current may be carried by charged atoms or molecules, we shall jump to the conclusion, amply justified by the experiments we are now discussing, that we can regard the important free charges in the ionosphere as electrons only; this will shorten the story without leaving out any essential truths. Now, just as wireless waves are sent out by vibrating electrons, so, conversely, do wireless waves set electrons into vibration. If then we send a wireless signal into the ionosphere, the free electrons there will vibrate at the frequency of the ingoing wireless wave. But a vibrating electron sends out a wireless wave, and so these electrons, set in motion by the ingoing wave, send out an outgoing wireless wave of the same frequency. Whether that outgoing wave is noticeable by us at the ground floor depends on several things. The individual electrons must be suitably arranged for their individual tiny wavelets to add up into a reasonably strong combined wave train. And that wave train

must be able to travel without being heavily absorbed in the parts of the ionosphere which it must traverse. The first condition proves on closer examination to demand that there must be a sufficiently large number of electrons in every cubic inch of the storey concerned, and this "sufficiently large" involves more electrons for a short wave, that is for a high rate of vibration, than for a longer wave of lower frequency. The second condition means that these required numbers of free electrons must exist in places where there is no overcrowding by atoms and molecules of air. For if there are many molecules closely packed the vibrating electrons will cannon into them, and be abruptly brought to rest, wasting their energy of motion in making the molecules move a little more vigorously, which is merely another way of saying that they waste their energy in heating up the air instead of putting it into the sending of outgoing wireless signals.

If these conditions are fulfilled the free electrons will manufacture an imitation of the ingoing signal, and the imitation will come back to us as an echo. The imitation may be a very good one indeed, so that we can treat it as if it were the original signal, but we shall see in a moment that it is not always a perfect imita-

tion. The description just given may not, at first glance, appear to have much to do with mirrors, but, in fact, it describes a process very like that which takes place when the short wireless waves called light waves strike a mirror. The electrons in the mirror manufacture new waves which add together into such a good imitation of the original that this "light echo" from the mirror can be treated as if it were the original wave reflected from the mirror surface, and is so treated in the ordinary theory of optics.

We may, then, picture the tenth floor or eleventh storey of the Weather House as having a floor marked by a rather abrupt change from comparatively few electrons per cubic inch, badly jostled by crowded molecules, to comparatively numerous electrons with more elbow room. Nothing we have yet said demands this abruptness, but experiment shows that since a large range of wavelengths seem to be returned to us from the same level the change is actually abrupt. Our picture may now be completed by a rapidly increasing concentration of electrons as we climb upwards, with a further thinning out of the obstructive molecules. If now a wavelength too short to be "reflected" at the floor level goes a little

higher in the storey it will find enough electrons to turn it back earthward. Here, however, we meet an effect which was mentioned early in the chapter. If the waves do not come back from the tenth floor of the Weather House they very seldom come back from the eleventh or twelfth, they may occasionally come back from the thirteenth, but they usually shoot straight up to the twenty-second floor, to come back earthward from there. If, however, they are short enough waves they may shoot clean out through all these storeys, and escape from the Weather House altogether—through the looking glass!

The troposphere is a single storey of the house, so is the stratosphere. The ozonosphere is a flat which occupies more than one storey, it shares the stratosphere and we know very little about its higher storeys. But the ionosphere is clearly a large and commodious flat, extending from the tenth floor to an indefinite height, far beyond the twenty-fifth. There are about twenty million free electron tenants per cubic inch of the tenth floor during the daytime; after the sun has set the number goes down to about a tenth of the noonday number. The tenth floor is the Kennelly-Heaviside region, named in honour of the two men who

independently suggested that it must be there to account for long-distance wireless communication, one of them a professor at Harvard, though born in Ceylon, the other one of the most distinguished independent workers England has ever given to electrical science. The two storeys above this Kennelly-Heaviside region have, as we have seen, fewer electron tenants, but the crowding increases again in the thirteenth floor, in the very recently discovered "intermediate region" as it is called, from which waves are sometimes returned, after getting through the Kennelly-Heaviside region for lack of electrons to turn them earthward. Then again the population goes down in numbers, until about the eighteenth floor another sharp increase is reached. Between the eighteenth and the twenty-third there is a further increase in the number of electron tenants, till, in the twenty-third itself there are about five times the number per cubic inch that there were in the tenth. Above that the crowding goes down again, but we do not know a great deal in detail about these highest floors. This twenty-third floor is the Appleton region, named after the young professor of physics at King's College, London, who discovered it in 1927.

There are two complications in this story of

the ionosphere which we have not yet faced, and it is doubtful whether we need spend much time over them, important though they are to wireless listeners. One is that wireless waves travel slower in the ionosphere than in the lower storeys of the Weather House, and that this reduced speed also depends on wavelength. The other is that the electrons in the ionosphere do not vibrate in straight lines, as they would do were the earth not a magnet, but curl round the " lines of force " of the earth's magnetic field so that they vibrate in oval or circular paths. This puts spin on the " imitation " waves returned to earth, and it was for that reason that we remarked that the imitation was not perfect. Indeed it very frequently happens that the single original wave is replaced by two sets of waves with opposite spins, of which one comes from a slightly higher storey, and at a slightly lower speed than the other, so that a signal which went up single comes back as right- and left-handed twins.

We have studied the density of crowding of the electron tenants, we have said neither how we count them nor how they got there. The counting process is, indeed, implied in what we have already said. We can, by our echo-sounding, find the wavelength which is just

not returned from a given height, and from knowledge of this critical wavelength we can easily calculate the number of electrons per cubic inch at the height in question.

The vast majority of the electron tenants of the ionosphere are aboriginals. The ultraviolet light from the sun shakes them out of the air molecules, they are constantly recombining with the positively charged remainder of these molecules, but the shaking apart outweighs the recombination (and the attachment to neutral molecules) as long as the sun is shining on the region considered. After sunset, however, the recombination process is not balanced, and the number of free electrons decreases.

There are, however, relatively small but still important incursions of strangers, of visitors from abroad into the ionosphere. We are under promise since chapter XII to talk about them. The magnetic storms and disturbances which opened this present chapter are known to be very closely related, on the one hand, to the state of the sun, and on the other to the appearances of aurora polaris (aurora borealis for us, aurora australis in the southern hemisphere), the nothern lights or merry dancers. It is now known that magnetic storms and

auroral displays are most in evidence when there are large sunspots to be seen, although the visible markings which are called sunspots have now been absolved from direct connection with these disturbances. Everything fits, however, with the working picture of an invisible gun on the sun, which goes on for some months at a time firing minute projectiles outwards, and scoring hits on the ionosphere when the rotation of the sun on its own axis (round which it turns in about twenty-seven days) brings the gun to bear on the earth. The bore of the gun is enormous, much bigger than the earth's diameter and the projectiles keep together in a stream like the jet from a hose. There must be equal proportions of positive and negative charges in the jet, else it would spread out and become ineffective. The earth's magnetic field will, however, do some sorting out of the charges as they get near the earth. This jet of tiny missiles pours into the ionosphere, and in addition to its own content of free charges it produces large numbers of additional free electrons by the shattering process we have already discussed in Chapter XII, the process of ionization by collision as it is called. We saw in that chapter, too, that the shaking up of electrons in the atom or molecule results in

the giving out of light ; the light of the aurora is the result of this ionization and closely related processes. We can, by simple trigonometry measure from simultaneous photographs taken at two stations on the same point in an auroral drapery the height at which the auroral arcs and curtains hang. It is very significant that their lower edges are trimmed very neatly at the floor level of the Kennelly-Heaviside storey ; the sharpness of the trimming, on the average, shows that there is a very marked change in the state of the house there. The exceptions to an average rule are, however, often more important than the rule, and there is much to be learnt from measurements such as those made at Tromsö in March 1933 (at a moment when, as it happened, the writer of this book had the good fortune to be at the Tromsö Auroral Observatory) showing that on occasion the auroral curtains may trail their hems as low as the sixth floor of the Weather House.

The combination of radio echo-sounding, of magnetic disturbance measurements, and of observations on the light of the aurora promises to make us much more familiar with the state of the atmosphere from the tenth to the thirtieth storey than with that of the fifth to the tenth, for example. Meanwhile we can

say, by way of illustration, that while the radio methods can count the electrons, the light of the aurora tells us definitely of the presence of oxygen at these high levels, and indeed at the highest level at which the aurora has been measured, at the hundredth storey, where ends our definite knowledge of the Weather House. If the Union Jack and the Star Spangled Banner float side by side on the tenth floor, the Union Jack alone on the twenty-third, the white cross of Norway on its red ground has a proud place on the topmost storey known to us.

These observations on the fine details of colour in the light of the aurora—the spectroscopic analysis of that light—and of the somewhat different and very faint light from the night-time sky when there is no auroral display, are important in telling us about the mixture in these high storeys of the ingredients which we discussed, for the first floor, in Chapter XVI. They show that the air movements we sampled in Chapter XVIII are sufficiently vigorous to prevent the sorting out by weight, which had been thought possible in the first floor, from being effective even in the fifth and higher floors. They show that nitrogen and oxygen are still the principal tenants,

though very recently indeed traces of the presence of the very light helium and the comparatively heavy argon have been detected, probably above the tenth storey. Hydrogen, whose lightness was expected to bring him into importance as an upper-floor tenant, has not yet been detected there, and it seems not impossible that instead of staying there he has escaped into outer space, that he too has gone through the looking glass.

XX

THE LIGHTING SYSTEM

THE Weather House is lit, as it is heated, by wireless from the sun. We have already seen that there is a certain range of wavelengths for which our eyes—and the eyes of all the animal kingdom—are ready-tuned wireless receivers. Not only do we appreciate through them the rays coming from the sun directly, but we appreciate also the rays turned towards us by the reflecting surfaces of the moon and the planets, our neighbours in Sun Street, and by reflecting surfaces in the Weather House itself. The colours of things as we see them are determined by the things acting as selective receivers, absorbing some wavelengths and converting their energy into heat, reflecting the remaining wavelengths, whose combined effect is that of white minus the absorbed, that is of the "complementary" colour.

It is scarcely necessary to discuss in detail how the intensity of sunlight varies throughout the day and the year, and from equator to pole ; these facts common to astronomy, geography and meteorology may be taken for

granted. Yet there are one or two points that are worth special notice in relation more particularly to the upper floors of the Weather House. The first is that the intensity of sunlight, even before it enters the Weather House, seems to vary somewhat from time to time. That there is a slow variation, that in fact the sun is a variable star, and a variable star of the kind that changes in colour, seems to be definitely established. That the less regular fluctuations alleged to take place at shorter intervals are real is not yet certain. The difficulties of interpretation, due to our inability to get outside the Weather House, are very great, and it may be that these quick changes take place inside and not outside the House.

The second point requiring special notice is that the days are longer in the upper storeys. Sunset is, of course, due to one place getting in the shadow of the hump of the earth which lies westward of it ; sunrise is due to the emergence of the observing station from the shadow of the great hump of the earth to eastward of it. When the sun sets in the western sky of London it is not the sun that sinks below the horizon, it is London that sinks below the straight beam of light that is cut off by that horizon. And as day comes round again

London is lifted out of the pit of darkness into the shafts of light that have been steadily pouring across the point in space to which it has thus been lifted up by the spinning of the Weather House on its axis. And long before London itself is lifted into light the part of the ionosphere immediately above it was in the sunlight, long after London sinks into darkness the ionosphere is still above the shadow of the Atlantic. Particularly in polar regions do these differences between the length of the day at ground floor level and in the upper storeys become acute, the tenants of the ionosphere have far more midnight sun than do the ground-floor people.

The decorative lighting effects of the Weather House are in the main ground-floor effects. The softly luminous auroral draperies of the topmost storeys are, indeed, among the most beautiful of all these effects, but the daily magic of the blue sky, the nightly magic of a blue velvet " background " (which is, of course, a foreground) for the stars, is almost exclusively enjoyed in the ground floor, as are the very varied decorative effects, due to the cloud fabrics, which we shall examine after we have tried to answer the related questions, " Why is the sky blue ? " " Why don't the stars shine during

the day?" The second question is readily answered. They do. But when we have answered the first we shall understand why the second should be asked.

The cigarette smoker, looking at a lamp through his own puff of smoke, sees the light tinted reddish-brown. But the smoke, looked at from the side, is a rich blue, unless the smoker has first inhaled it; in that case the smoke is a brownish white. These three facts tell us a great deal about the colours of the sky. Very small particles, like those of the un-inhaled smoke, exercise a strong preferential action in scattering the light which falls upon them. The light which they turn aside, so that it can reach our eyes even though we are not looking straight at the original source of light, is very much more blue than the original light. In fact from an original mixture of blue and red light in equal proportions the light scattered sideways would contain sixteen times as much blue as red. This blue turned aside is, however, taken from the original supply of light, and so that which passes on in the original direction is deficient in blue, it is, as we have said, reddish. But if the particles are not very small they have no such preferential action, and the light which they turn aside is very much the

same as the original light falling on them, although their reflecting power is usually not enough to give more than a rather dirty white from originally white light. We can thus conclude from a combination of theory and observation that cigarette smoke which has been inhaled and exhaled consists of much larger particles than ordinary cigarette smoke.

The blue of the sky is, then, blue light scattered aside from very small particles of some sort, variably mixed with white light turned aside by large particles. The red of the setting sun is white light which has lost its blue sideways by scattering, and which thus reaches us, by the direct route, as red light. There was for a considerable time a doubt as to the nature of the minute scattering particles, but it is now clear that we need not assume that anything more than the individual molecules of pure air are needed to give the blue, for the amount to which the colour of the direct light is altered by molecular scattering alone can be calculated, and has been shown to agree very well indeed with measurements made at a mountain observatory lifted above the dusty valley air. At these mountain stations the colour of the sky is a much deeper and purer blue than down below, because there

are fewer large particles to give an admixture of white light. It was, then, to be expected that the stratospheric explorers would bring back reports of sky colours which would be at once picturesque and helpful in confirming our expectations about the comparatively dust-free state of the first floor.

We have acquired a working idea of the reasons for the blue of the sky, and for the red of the sunset. We know that the stars shine by day, but that we have difficulty in seeing them because of the scattered light from air molecules, dust particles, water droplets, and ice crystals in the ground-floor atmosphere. We can see why the snow slopes facing the rising sun are flushed with pink, for they are reflecting the red of the sun's rays which fell on them after losing blue by scattering. We can see why the deep shadows in the mountain landscape are blue, because the blue scattered from the layer of air between us and the mountain side is clearly visible to us against the dark background. It may be worth saying in passing that the success of infra-red landscape photography is due to the infra-red sensitive plate ignoring the light scattered from the air between it and the distant scene. We are prepared for very great variations in sky

colour down near the horizon, because of the very thick layer of dusty and vapour-laden air through which the light rays travel to reach us from these low angles. We shall expect these colours to carry a story, if only we can read it, about the state of the air. The many signs and sayings connecting these colours with the state of the weather arise from these effects of suspended particles, but the story is at once so complicated and so incomplete, and refers to such a small sample of the ground-floor furnishings, that we can do very little weather prediction by colour code.

There is, however, a whole sequence of decorative lighting effects which adorn the Weather House in a fine sunset without being so brilliantly obvious as the red of the setting sun itself and of the clouds round it. The " green ray ", a brilliant emerald coloration of the very last edge of the setting—or the very first edge of the rising—sun, is, perhaps, a little difficult to observe satisfactorily over an ordinary European landscape, although it is no longer at the mercy of the sceptic. But there are normal sunset effects, at once more readily seen and more subtle than those others, which go unnoticed for want of knowing when and where to look. Turning your back directly

to the setting sun as it sinks below the horizon you will see, rising in the cloudless east, the " first eastern twilight arch ", the very shadow of the rounded earth ; above the arch the sky is still a luminous blue, the arch itself is faintly purple, and below it the blue is a much duller blue because the sun's rays are no longer penetrating into the shadow zone to be scattered back to us. When the sun sets behind a prominent mountain peak the arch has a tooth corresponding to the shadow of the peak. As the sun sinks steadily further below the western horizon the eastern arch rises in the sky, in a picture which is the more impressive because of its low tones and its colossal restraint.

By this time the bright sun is well set, and eyes rested by looking eastward may be turned westward without being dazzled, without losing their sensitivity to the infinitely tender colour and fairy velvet texture of the " purple light ". Soon after the disc of the sun had disappeared a patch of silvery brightness appeared in the sky above it, at a height which can be measured by holding out a stick fourteen inches long at arms length. As the sky darkens still further the patch seems to brighten, to take on a pinkish purple tone, and to spread, so that soon we have a whole gothic arch of soft purple light

resting on the spot where the sun set. Gradually it sinks and fades, to be followed by a second and fainter arch, as, indeed, the eastern arch had too a faint successor.

A chapter on decorative lighting cannot, despite its growing length, fail to say something of other sky signs, the big ring and the little ring round the sun or moon, the rainbow, and their close relative the Spectre of the Brocken. The big and little rings tell very different stories. The big ring, the solar or lunar halo of 22 degrees, is a milky white ring with a browny-red tinge on its inner edge, which occupies (in a military sense) about a quarter of the visible sky, and which is notable as the boundary of a curious contrast in lighting. For the sky just inside the ring, despite the sun or moon at its centre is notably darker than that just outside it. The 22 degree halo with its rarer giant brother the halo of 46 degrees tells of ice particles at the cirrus level, and the 22 degree halo tells of hexagonal ice crystals, while the 46 degree halo tells of rightangled crystals. Only crystals give halos, and each shape and aspect of crystal makes a characteristic contribution to the halo pattern. Bright patches at the level of the sun or moon, " mock suns " or moons, tell of myriads of tiny ice prisms floating with their long axes

vertical; there are mock suns which tell of the presence of clouds of crystals each shaped like a cubist collar stud. The halo has its place in traditional weather lore as a precursor of storms, but it is not to be regarded as an exceptional portent, it tells only of cloud at the cirrus level, cloud that may be almost invisibly thin ; such information is a valuable item in the whole mass of information about the weather of the moment, but it is only one item of many.

The small ring, again solar or lunar, but most clearly seen round the moon because of the absence of glare, is less intense, perhaps, but at once more delicate and more colourful. The lunar corona is not a single ring but a whole succession of rings of different colour, a target with the moon as the bull's eye. The " inner " is bluish-white, the " outer" brownish, but outside these small areas of impure colour are rings of blue, green, yellow, with red on the outside. The corona tells of water drops, not ice crystals, in the atmosphere ; the size of any particular ring tells us the size of the drops ; the purity of the colours tells us about the assortment of drop sizes. Very pure colours mean well-matched drops, nearly all of one size ; this suggests a very young cloud. The

smaller the drops the bigger the rings, so a corona that is growing larger tells of drops evaporating away, a shrinking corona tells of drops growing larger by condensation. It is by corona effects that we infer that the mother-of-pearl clouds of the second floor are probably water clouds.

Much nearer home in our own ground floor than the halos and coronas is the rainbow; but not so near home as is suggested by songs about " a rainbow round my shoulders " and by letters to the editor about driving a motor car under a rainbow. "A rainbow is seen," says the Meteorological Glossary, " when the sun shines upon raindrops. The drops may be at any distance from the observer from a few yards to several miles." The light is reflected from the raindrops, so the rainbow is only seen when the sun is more or less behind the observer; the light comes back concentrated in a certain preferred direction, and so the bow has an angular radius of about 42 degrees; it is a bit of a circle with its centre at the point exactly opposite the sun on a line which passes through the sun and the observer. Thus a high sun gives a low rainbow, of which only the top may be seen, but a setting or rising sun gives a full semicircular rainbow. This

fixed angular radius for halos and rainbows is important, and is worth looking at in another way. If one holds out at arms length—which we take as twenty-four inches—a stick which is twirled about one end, the other end makes a circle of fixed angular radius. If the stick is nine and a half inches long it will mark out the size of the 22 degree halo, if twenty-five inches, the 46 degree halo. There are still rarer halos corresponding to sticks four inches and eight inches long.

A stick twenty-two inches long will mark out the size of the primary rainbow, a secondary bow with the colours arranged in opposite order is often seen at a radius corresponding to a thirty inch stick, the space between the two bows is darker than that inside the primary or outside the secondary. The exact arrangement and width of the bands of colour tell us about the sizes of the raindrops producing the bows. There are two reasons for seeing " white rainbows ". One is that by moonlight the colours are so faint that the eye fails to distinguish them as colours, and reports white only. The other is that with very small water drops indeed the colours are confined to the edges of the bow, while the main part of it is white. This gives us the fog bow, for reasons which will be obvious.

In the fixed angular radius which we have just discussed lies the catch about shoulders and motor cars, and, saddest of all, of course, about pots of gold. If the observer walks forward, with his measuring stick held in front of him the bow walks forward, if he runs, it runs—no faster—if he stops, it stops, always the rainbow is as far in front of him as it was.

The Spectre of the Brocken is the shadow of the observer himself, cast upon a fog bank when the sun or moon is behind him. It seems large because he overestimates its distance, and the shadow of the head may be surrounded by a " glory ", a rainbow-like group of coloured rings which may, for example, run thus, centre whitish-yellow, then dull red, bluish-green, reddish-violet, blue, green, red, then green and red again. Outside all may be the white fog bow already mentioned.

This decorative lighting is a temptation to disproportionate lengths, it is one of the unfailing joys of the Weather House. But of all its charming subtleties there is none more seductive than that of irisation, the very delicately tinted patches of complementary colour that appear on high cloud, especially on alto-cumulus, near the sun or moon. It may very often be traced on thin alto-cumulus if the

direct glare of the sun is shaded off, the most frequent colour combinations are apple-green with a pink edging, or an ochre-yellow with a singularly acid steel-blue edging.

But there may be, after all, no decorative lighting in all the Weather House—save perhaps the soft electric lighting of the aurora—more soul-stirring than the infinitely tender green-blue of the northern sky at sunset. There are souls and souls, however, and it was a very distinguished soul who thought it right to call his classical paper on the theory of the rainbow "On the Intensity of Light in the Neighbourhood of a Caustic".

XXI

THE SERVANTS' QUARTERS

THE servants' quarters in the Weather House deserve more than a passing glance. There the slaves of the weather map are charged with the never-ending task of knowing what is the weather of to-day, of remembering what was the weather of all our yesterdays, of estimating what will be the weather of to-morrow. They have a language and a tradition of their own. Lerwick, 11052, 02634, 22577, 28846. Spitsbergen, 000xx, 372x9, 29719, 06167. Moscow, 90900, 47x90, 28206, 34770. The teleprinter and the message tubes on the fifth floor at the Air Ministry give out gushes of messages like that soon after 7 in the morning and 1 in the afternoon; and just as the 6 p.m. forecast is coming out of your loudspeaker the raw material for another forecast is beginning to pour into the Meteorological Office by telephone and by teleprinter. Between these high peaks of the meteorologist's day there is a constant stream of information flowing in.

Even the meteorologist is inclined to forget what the full story carried by these cypher

messages is. It is only occasionally that he can sit back, look quietly at a group like this "1106x, 64658, 22658", and think at length of all it says. It means that at five to seven that morning an observer at Lerwick pulled on coat and hat and gloves, picked up his notebook and electric torch, and went out to look at the weather. He found a strong west-south-westerly breeze blowing to him from the Atlantic, and so, despite this early hour of a February morning in the Shetlands—the sun would not be up yet—it was mild and moist, just how mild and moist he would measure in a few minutes. He knew the wind was a strong breeze, about 27 miles per hour, not just a fresh breeze, not so much as a moderate gale, because of a number of little signs he had learned to use in estimating wind strength, signs which include smoke drifting and leaves rustling, branches swaying and slates falling; but for a dearth of suitable trees and leaves he could have judged the 27 miles per hour from his book of the words which says: "Fresh breeze—small trees in leaf begin to sway, crested wavelets on inland waters." "Strong breeze—large branches moving; whistling in telegraph wires, umbrellas difficult." (Not that any reputable meteorologist would carry an um-

brella at seven in the morning.) "Moderate gale—whole trees in motion; hard walking against wind." His sky was completely covered with nimbus—the continuous rain guaranteed it as nimbus—and by experiences which included sending up toy balloons and seeing how long it took them to get lost in clouds, he could judge pretty accurately that the nimbus was 800 feet up. The air was moderately clear; familiar landmarks told him that he would be able to see six miles or so, not merely the two miles or less of "poor visibility", not so much as the twelve of "good visibility". Rain had begun since his last observation—it was only half clouded at 1 a.m.—the water collected in the measuring-glass inside his copper rain-gauge showed a fifth of an inch had fallen. Emptying the glass, putting back the collecting funnel, he had turned from the rain-gauge to the whitened wooden "meat-safe" that held his thermometers four feet above ground. His electric torch showed the "dry bulb" as indicating an air temperature of 44 degrees F.; the "wet bulb", as he expected, was hardly a trace lower, the air was very nearly saturated with moisture. He then read the very cunningly simple thermometers that leave an indicator at the highest and lowest temperatures they

reach during the day and night, 40 degrees and 34 degrees this morning, then he shook the indicators back to start their job afresh, made seven o'clock time marks on the recording instruments in case the clocks carrying the record were going fast or slow, and went indoors again to read his barometer and his recording aneroid, all this, as nearly as possible, on the stroke of seven. The barometer reading had to be "corrected" for the temperature of the mercury; the aneroid told him that "the glass" had fallen 8 millibars, 2½ tenths of an inch, in the last three hours, to reach its present level of 1001 millibars. And then, having taken a blue card out of the sunshine recorder, another cunningly simple device, with a glass ball which acts as a burning glass, concentrating the sun's rays on the card and burning a trace on it so long as the sun shines, he measured the sunshine score for yesterday, 5.9 hours, pretty good for a February day in the Shetlands.

The Daily Weather Report contains more than two hundred "human documents" of this kind for every fixed hour of observation, 7 a.m., 1 p.m., 6 p.m., telling the experiences of the great meteorological brotherhood scattered all over the map of Europe, all, at the

same hour—well nearly at the same hour—doing the same thing to similar instruments, writing telegrams in the same code, and sending them off with urgency to their central offices. At very nearly the same moment as in Shetland the man in Spitzbergen was thawing his stiffened fingers to telegraph about a temperature of —8 degrees F. in a calm under a cloudless sky, with a crisp air in which he could see more than thirty miles. An hour later by a London clock, but a good deal later by his own clock, a comrade in Moscow was stamping through the snow, which was still falling, though slight, to read a temperature of 32 degrees F., just freezing, warmer than yesterday's highest of 28 degrees F., though it had got down to 23 degrees F. a few hours before. His sky was overcast, but the snow was falling from clouds about 4000 feet up.

Two hundred documents means tabulated statements, but the so-called British section of this amazing weather newspaper, which reaches us in London on the evening of the day whose morning weather it records, and which is all over Britain in next morning's post, is still more thrilling. It contains a chart of weather in the northern hemisphere which gives you shorthand pictures of what men were doing

and feeling at the same time up the Nile, out along the trans-Siberian railway (twenty degrees of frost and a clear sky at Vladivostock), on ships on the high Atlantic (snowing at Cape Race), and all over North America (twenty degrees of frost in Nantucket, sixty degrees of frost near the southern end of Hudson Bay).

It is a picture that should be alive in our minds, this daily international co-operation, this triumphantly silent running of a meteorological League of Nations that was working long before the Geneva days. Into London, Paris and Berlin, into Oslo, Stockholm, Warsaw, Helsinki, Moscow and Washington, these telegrams flow, speaking a universal weather language of astounding compactness, and in all these and many other places they are decoded and built up into weather maps where, long before noon in London, you can read the news of the 7 a.m. world. And again these weather maps are in an international shorthand. Soar as it may into the heavens, the Weather House has outlived the Tower of Babel.

It is on these maps that the forecaster builds up his pictures of battle-fronts and isobaric systems ; though we have contrasted the two kinds of picture most forecasters, including the Norwegians, use both aids to complete repre-

sentation. Charts of isobars and air masses and fronts, and sometimes charts of "isallobars", that is of areas of equal change of barometer height, separate charts of cloud systems, and—very important nowadays—diagrams showing the temperature conditions read by specially fitted aeroplanes making meteorological flights, and other diagrams showing the wind strengths up to the cloud levels, measured by the toy balloons mentioned before; all these pictures the forecaster draws to help him towards estimating what the weather of tomorrow is to be like. And they have to be drawn on the top of maps showing the geographical features of the land and sea, because the height and steepness of mountains, for example, have a great effect on weather-making.

Why, with all this elaborate machinery of observation and high speed interchange of information by line telegraph, by telephone and by wireless, with all the study that has been given to the physics of meteorology, are the forecasts limited to short periods, seldom over twenty-four hours, and why are they sometimes incorrect even for these short periods? And why do they sometimes sound vague and almost "hedging" to the ordinary listener? First

there is a general reason applying to the world as a whole. Despite the fact that observations up to the ground-floor ceiling can now be made, they can only be made occasionally, far less frequently and at far fewer places than would be required for a really detailed knowledge of the state of the weather layer at each of the fixed hours of observation. We cannot yet conceive as practically attainable a state in which there are enough aeroplane ascents to provide this missing data about the weather layer. It is true that *radio sondes*, *ballons sondes* which automatically report by wireless as they go aloft, have been used in the recent Polar Year observations. But they are too expensive to be very widely used ; at best the cost could only be justified if they provided results with regularity and certainty, and if the risk of loss of the instruments could be much reduced.

The next reason applies with special force to our own islands. There are parts of the world where the run of the weather is so regular that forecasting is usually quite an easy job, even the forecasting of disturbances. That a hostess in the West Indies can invite you for an afternoon visit and say " Come before the thunderstorm " illustrates this kind of thing. But here in the cockpit of Europe we have great vari-

ability, and that variability is largely controlled by things happening in the Arctic regions, and out in the Atlantic. Very important members of the family of air rivers are the cascades of air which flow down from the icy plateau of Greenland into the northern Atlantic ; the forecaster who sees evidence of a fresh off-flow of cold air from Greenland looks out for the formation of new low-pressure systems in the Atlantic. But the number of observing stations in the Arctic is disappointingly though necessarily small, while even the immense and comparatively recent advantage of wireless reports from ships leaves us still very doubtful of the day-to-day details of Atlantic weather.

The task of the forecaster is to recognize the weather situation of the moment and how it came about, to identify the important features of the situation and estimate how they will travel, how they will change in travelling, and what effects will be produced by the nature of the country over which they travel. We, in Great Britain, with our weather coming up to us from the Atlantic are handicapped by not knowing very much about new features until they are near our western seaboard ; our Continental neighbours have the advantage that we act as a forward observation post for

them ; they get our cast-off weather, although they have their own troubles in estimating how it will fit itself to their country.

The failures of the forecaster are due to the mis-reading of inadequate signs and symptoms ; his apparent "hedging" is only apparent—those who have learned to listen to the forecasts know that phrases like "local mist or fog" and "showers in places" are more definite than they seem. The forecast prepared in a central office is, in fact, only intended to guide the local forecaster, professional or amateur. Forecasting for a particular place can only be done effectively by a scientific meteorologist with intimate local knowledge, one who knows how his district moulds its own weather supply out of the general situation. The important work of aviation forecasting is done in this way : each important flying centre has its local forecasting centre working with all the information that the Meteorological League of Nations can give it, but applying the information with a full knowledge of local peculiarities.

In no science has the amateur a more important place. The British Rainfall Organization, and the Thunderstorm Census are good examples of co-ordinated amateur work, while

the Royal Meteorological Society blends the interests of a great preponderance of amateur and a handful of professional meteorologists very happily and successfully. The future of weather science depends not so much on the professional as on the public ; the facilities for meteorological research in Great Britain, despite its very creditable record, are preposterously inadequate. Its future depends on public interest and support.

XXII

DOMESTIC ECONOMY OF THE WEATHER HOUSE

THE scale of the vast housekeeping operations that have faced us in our first twenty chapters is not adequately brought home to us by the sizes and weights of rooms and furnishings that have found their way, more or less accidentally, into our survey. It is salutary to look at the housekeeping books in some detail before we turn, in a later chapter, to look at some of the proposals for refurnishing that are lightheartedly put forward by exponents of a New Deal in the Weather House.

We know already that one side of the account book is occupied wholly by wireless income from the sun, casual windfalls brought by the other visitors from abroad just aren't worth bringing into account. *De minimis.* . . . As a bookkeeping artifice we shall convert all the stuffs with which we have to deal at a fixed rate of exchange which is a little off the current gold standard, we shall count electrical energy delivered to the consumer's premises as being worth a penny a unit—something of an

overcharge, but familiar enough and easy enough to figure with. And just as this universal fluid at a penny a unit is turned to many uses, to lighting and heating and cooling and washing and cleaning and sound-reproduction and to industrial processes, so we can think of the electrical value of all the mechanical and hydraulic processes in the Weather House, and put the prices on the other side of the account in terms of the universal penny a unit.

The incoming wireless programme from the sun is, at the roof of the Weather House, before parts of it have been tapped off by the upper-floor tenants, worth £87,500 per square mile per day, on the acreage of the whole house and the whole year. The extent to which any Danaë in the house participates in this very generous golden shower depends, of course, on the latitude in which she lives, and varies with time of the year. The roof over the English Channel enjoys a total annual income of nearly £27,000,000 per square mile, as compared with £39,000,000 at the equator and £16,000,000 at the poles. The total daily income in the Channel area varies from about £18,000 at Christmas through £75,000 at the equinoxes to £120,000 a day at midsummer.

We shall be unable to discuss the accounts

further in relation to a particular area, we shall have to strike very rough balances for the House as a whole. We note first that the house modestly refuses to accept the whole of the proferred wealth, it reflects back towards outer space, without any modification, something between a third and a half of the incoming radiation, so that the average daily income which it accepts is about £50,000. The reflecting power of clouds accounts for the rejection of just under a third of the income, reflection from the air itself rejects a twentieth, while that from the floor of the Weather House accounts for a rejection of only about a fiftieth of the income.

Of the accepted £50,000 the atmosphere borrows, temporarily, an amount which we shall consider along with some other items in the balance sheet. The remainder gets through to the floor level and averages about £37,500 per square mile. This is available energy for heating the floor and the air in contact with it, and for evaporating water from the floor.

The accounts are made distinctly difficult by the complicated borrowing and paying back between the air and the floor. If we took out a balance sheet for the atmosphere alone we should find three entries on the income side, there would be £87,500 from the sun, about

£65,000 from the floor, as terrestrial [illegible]ong-wave programme, and an additional £25,000 from the floor carr[illegible]y direct transport as heat, by conduction [illegible] evaporation. On the expenditure side would [illegible] four sums [illegible]ot very different from one another in amount—a few thousand pounds one way or another not mattering very much to us. One of these would be the unutilized income already mentioned, one the amount allowed through to the earth, the rest for a long-wave programme radiated from the warmed air itself, rather more than half of this going down to the floor, rather less than half going out into outer space again. As between atmosphere and floor, then, the accounts show the atmosphere paying back to the floor only about half what it gets from it by the two processes of radiation and direct heat transfer.

For the House as a whole, of course, the accounts must balance accurately, the whole of the £87,500 per square mile in the incoming programme from solar regional goes out again as terrestrial regional programme; the important things in weather-making are the ways in which the energy is transformed before it finally goes outward again as long-wave radiation. The balancing does not hold for any

one bit of the House alone, there are transfers among the ground floor tenants, but for the whole House it holds [illegible] merely over the whole year but prett[illegible]urately month by month.

There we leave the general balance sheet, but it is still worth considering some more intimate details of the household economy. How, for example, is strong summer sunshine related to the figures we have discussed, what is the price of an inch of rain, what does it cost to make a gale, what ought one to pay for a deep depression over Iceland? And, lastly, can we put down a fair price for buying lightning flashes by the yard? We take these questions one by one.

The first really asks how the strongest sunshine in England compares with the overall averages which we used in our balance sheet. The income in this case can, of course, be measured directly by a suitable instrument, and the result of the experiment is that the income in strong summer sunshine in England is something over £10,000 per hour per square mile, say £133,000,000,000 to buy an hour of bright sunshine for the British Isles.

The municipalities of the British Isles would gladly have bought rain in the drought of

1933-34, what would have been a fair price? Suppose the population of Middlesex were to subscribe for a year's average rainfall over the 283 square miles of the county? The weight of rain required would be about 500 million tons. The main cost would be in evaporating the water required; the cost of lifting it up the cloud staircase and transporting it to the place of delivery is negligible in comparison with the boiler-house costs. These amount to 700 units per ton, so that we require very nearly £3 per ton, or £1,500,000,000 to provide this very ordinary water supply. In both the examples quoted we might reasonably ask for a better rate than a penny a unit in taking our bulk supply of electricity, but it would be unreasonable to expect that we could cut these alarming figures to anything much under a quarter at the best; we could scarcely get below £400,000,000 for our year's rainfall.

The price of a gale is less amenable to calculation. The energy stored in a ton of average gale is relatively inexpensive, it is worth a seventh of a penny. The real difficulty comes when we try to estimate how many tons are carried along at 45 miles an hour in the torrent of air which we call a gale. The best we can do is to consider what value is represented by

a bit cut out of the whole gale. How fast, for example, would our penny units flow over London Bridge in a westerly gale which had a speed of 40 miles per hour at floor level and hurricane speed—as it certainly would—at the top of the cloud staircase? London Bridge is 928 feet long, the torrent of air is about six miles deep, this means some 400 million tons of air passing per hour, total price £200,000 per hour.

Sir Napier Shaw has calculated the quantities involved in a very modest little depression which formed over the North Sea at the end of July 1917. Its diameter was about 900 miles, and in its formation seventy thousand million tons of air were removed in about six days, returning in about another three days. The quantity of water-vapour in the area he computes at 700 million tons, and the energy of air motion developed would be valued, on our scale of a penny a unit, at a hundred and seventy million pounds. To put the water-vapour there, however, merely by evaporation, had first cost nearly two thousand million pounds on the standard price schedule.

Compared with these "astronomical" figures the price of a yard of lightning flash is very modest. A complete flash is worth about £15 at a

penny a unit, and it is about 2000 yards long, so that the price works out at about three halfpence a yard. This does not, however, allow for wrapping it up. It will be clear from the relative figures in this chapter that, spectacular as the lightning display may be, it does not, even at one flash per second as in a really severe storm, dissipate more than a quite small portion, ten per cent or less, of the stored-up energy represented by the "latent heat" of the water-vapour which occupies the express lift shaft of the thunder cloud.

As the last of these snippets from the account book we may turn back to Chapter XI and ask what sort of capital is locked up in the energy of motion of the general air circulation of the Weather House as a whole. It appears that this value is about £400,000,000,000, and that it is being dissipated by turbulence at a rate which would bring it down to a miserable four million pounds within a week. Fortunately, however, this is far from meaning that we are living beyond our means, it requires only the utilization of about 2 per cent of the income from the sun to make good the wastage.

XXIII

SAWS, SAINTS AND SAGES

We have seen something of the disappointments of the Victorian old masters, of the doubts and despondencies of the moderns, but there are other schools of painting at which we have not yet looked. There are the calendarists, with their patron saints ; there are the cyclists with their periodicities, their recurrence tendencies, and a whole ritual of weather cycles; there is the pastoral school of the Shepherd of Banbury ; and there are the Buchanites with their devotion to the magic of spells.

What about all this accumulated lore of very uneven quality ; what of the seven-day " forecast " by an anonymous " leading meteorological expert " ? What of red skies at night, hay for the cold, berries for a hard winter, of St. Swithin's forty days and of Buchan's fifth cold spell ? These, with the orthodox meteorology, are samples of different approaches to weather prediction. There is the weather sign, which is often right, but which fails to tell us enough, and which is not infrequently misleading. There is the scientific analysis of the

weather situation, which uses weather signs as part of its stock-in-trade, but which may have insufficient material or insufficient time to use it before the weather of to-morrow is upon us. And there is the merely superstitious and uncritical use of weather saws which, at best, contain a germ of truth so small, or so obvious, as to be of little use.

Any competent arithmetician will tell you the number of hands at Bridge which you must play, on the average, to have amongst them one five-honour hand. But the more competent he is the less likely is he to guess whether the third hand from now will be the one which gives you five honours in spades.

So the scientific forecaster has to estimate possibilities; the more his science advances the closer will his estimate become. But at this moment no scientific forecaster will so deceive himself and you as to give you a really definite forecast for more than twenty-four hours, and for more than a limited area; his refusal to state a " further outlook " in all save exceptionally favourable cases is an honest recognition of our present limitations. He can tell you, beyond the twenty-four hours, that on the average the 7th of March will be 4 degrees F. hotter than the 7th of February; but if you

ask him whether the 7th of March, 1935, will be hotter, at all, than the 7th of February, 1935, he must in honesty bid you wait and see.

The hay crop and the berry crop are determined by the weather of a year or more past, what the immediately coming weather will be in comparison with that past year, no honest meteorologist will yet pretend to know. There is, indeed, compensation on the whole, abnormalities are followed by compensating abnormalities, but when the compensation will come is beyond our present foresight.

As for St. Swithin, that great architect and clerk of the works, builder of churches and bridges, what is his relation to this Weather House of ours? Why does the meteorologist not believe that there will be forty days rain if St. Swithin's Day is wet? Not merely for the dull reason that, demonstrably, it is not true, but for the more amusing reason that it is grotesque. Because France has its St. Swithin, St. Medard, with his day on June 8th; we have Swithin, July 15th; the Belgians have St. Godelieve, July 27th. Meteorologically we are one family; where does this lead us? It rains on St. Medard, forty days rain goes on till July 18th, so it will rain on St. Swithin. Forty days from him takes us to August 24th, so it

will rain on St. Godelieve, and forty days from St. Godelieve takes us to September 5th. So, if it rains on June 8th, it will rain daily till September 5th. The argument is a little unfair for reasons which are readily seen, but only a very little unfair and on the whole it seems to me fair enough to be conclusive. And even so, superstition moves with the times. St. Swithin, rainmaker, has given place to Big Bertha and the B.B.C. ; gunfire and broadcasting have each, with equally little reason, been blamed for rainy spells. It requires little knowledge of the Weather House, or of its domestic balance sheet, to destroy all these superstitions.

XXIV

CONTROLLING THE WEATHER

THE account book, even the scraps of it which form Chapter XXII, is a sufficient answer to the megalomania which would have us intervene to control our weather by artificial means. Barking and Battersea are the London landmarks of present engineering achievement. The great electricity generating stations at these two places are a legitimate source of pride, yet they could be left out of the account book altogether. *De minimis. . . .*

The Barking station, if it devoted its whole activities to the manufacture of moist air, if it spent its thousand tons of coal a day towards rain-making only, could indeed, provide the raw material of rain-making, and means might be found for getting the moisture down as rain again. But what area could it serve? It could, by working at full load night and day, keep an area of little more than one square mile supplied with its customary rainfall, averaged out over the varied years.

The same kind of arithmetic applies to the clearing of fog, from an aerodrome, for example.

Shaw has calculated that it would take some hundreds of tons of coal per hour to keep a small aerodrome clear in fog conditions. The scale of all such operations is a scale beyond our normal, the Weather House is too large for us to refurnish out of available income. The word " impossible " is the most dangerous of words in a scientific household ; the words " too dear " are equally final in an economic household.

XXV

FURTHER OUTLOOK——?

THE Weather House has no roof, its story has no ending. Many of the chapters have finished " in the air ", for lack of full knowledge, and the survey will end appropriately in a mark of interrogation. Why is there lack of full knowledge ; why, in particular, is there such difficulty about a much desired foreknowledge ?

Grandeur of scale, physical inaccessibility and diversity of controlling factors are the three non-economic obstacles to progress. They bring with them the formidable economic obstacle that adequate original research on the Weather Houses and its furnishings would be excessively costly, and that a first step has scarcely yet been taken towards provision for adequate research. Some examination of these depressing statements may not be out of place in the last chapter even of this superficial survey.

We have already traced steps in the evolution of weather science ; we have seen something of these resurgences of optimism and enthusiasm

which came in the epochs of Fitzroy, Abercrombie, Shaw and Bjerknes. We have not, till now, had occasion to look into the remarkable book, at once inspiring in its courage and depressing in its conclusions, which Richardson has written on " The Numerical Computation of Weather ". The highest hope that he could offer was that a battalion of workers might, in six weeks from to-day, calculate the weather of to-morrow. Does this mean the twilight of scientific forecasting? Or does it merely mean that there is a piece missing from the jig-saw puzzle as it is placed before the workers?

There are, in fact, two very large groups of pieces missing. They may or may not prove to be key pieces, but it is certain that without them present methods cannot make very great progress. With them success is not assured; without them failure is foreordained. Both groups, as it happens, are of a nature which places the British Isles in an exceptionally difficult situation as a forecasting centre. The growth of shipping and communications has not yet rescued the oceans from their state as unsurveyed rooms of the Weather House. And yet the *tempo* of weather change is such that the weather of yesterday over the ocean is that of to-day over the land—with modifications.

The closest network of observing stations yet existing in a land area is not adequate ; the wide net of ship stations is quite hopelessly inadequate for maintaining a watch on weather processes at floor level.

But we have already seen that floor level is the least satisfactory of all levels for the study of weather processes. It is, indeed, at floor level that we enjoy or suffer our weather products, but the modifications imposed by the nature of the floor make the weather complicated. Could we make a full study of the weather a little further up in the weather layer we might be able to comprehend its relative simplicity, and then gradually to bring in the complicating factors which control the product as it reaches us on the floor. The key of the Weather House is to be found, if at all, well above the floor level; we have suggested that it may not even be found in the ground floor, but it will certainly not be found on the floor of the ground floor. Observations in the " free air " must be multiplied and scrutinized. Here the economic obstacle presses intolerably hard, for observation by aeroplane is expensive ; by *ballon sonde* or *radio sonde* it is inexpensive if we are sure of recovering the instruments, but the *ballon sonde* method is slow, since the recovery may

be delayed, while the *radio sonde* method has not yet been made sufficiently easy and certain. Both methods, above all the radio method, become very expensive when the instruments are lost ; an island country is unhappily situated for both methods because the instruments may so frequently be carried over the sea and lost there.

There is, however, another and perhaps even less cheerful way of looking at the future of weather forecasting. We have tacitly assumed that it may advance by evolution ; there is good reason for believing that the advance will come only by revolution. Some completely new method of attack, far more radically different from the current technique than was the Norwegian method from the older methods, may be required. It must, if that be so, come by inspiration, but the inspiration will only germinate in a disciplined scientific mind. There is more than good reason for doubting whether the ground is being properly prepared. The possible spheres of activity for the full exercise of a scientific meteorological mind are sadly restricted. On the one hand is the public weather service, charged with the public memory of the weather, charged, too, with the task of foreseeing the weather of to-morrow.

The task of forecasting was meant as a stimulus and a test, it has become a burden and an impediment. There must be somewhere a fable about an aspiring chick which, trying too soon to fly, crippled what had at least been a pair of perfectly good legs for walking. The public weather service is not, as things now stand, the best milieu for fledgling natural philosophers. On the other hand stand the universities, where the physical sciences are relatively lavishly endowed, and where life is not yet too crowded for thought. It is perhaps the greatest of all the disasters of meteorology that for all its intimate bearing on life, for all its obvious fascination, for all its scope for the bounding imagination, it has yet failed to attract to its exclusive service the greatest minds in physics. It certainly has not found its Newton or its Einstein, it is not obvious that it has found even its giants of the second rank of gianthood. And so long as there is, for instance, in the British Empire one, and only one, fully organized school of meteorology, turning out five students in a year, so long as even that school is detached from its main stem by standing independent of a school of physics, so long as a readership is the value set on meteorology by the major universities, the

prospects of a British Newton of weather science are unpromising. If no Newton whence the *Principia*?